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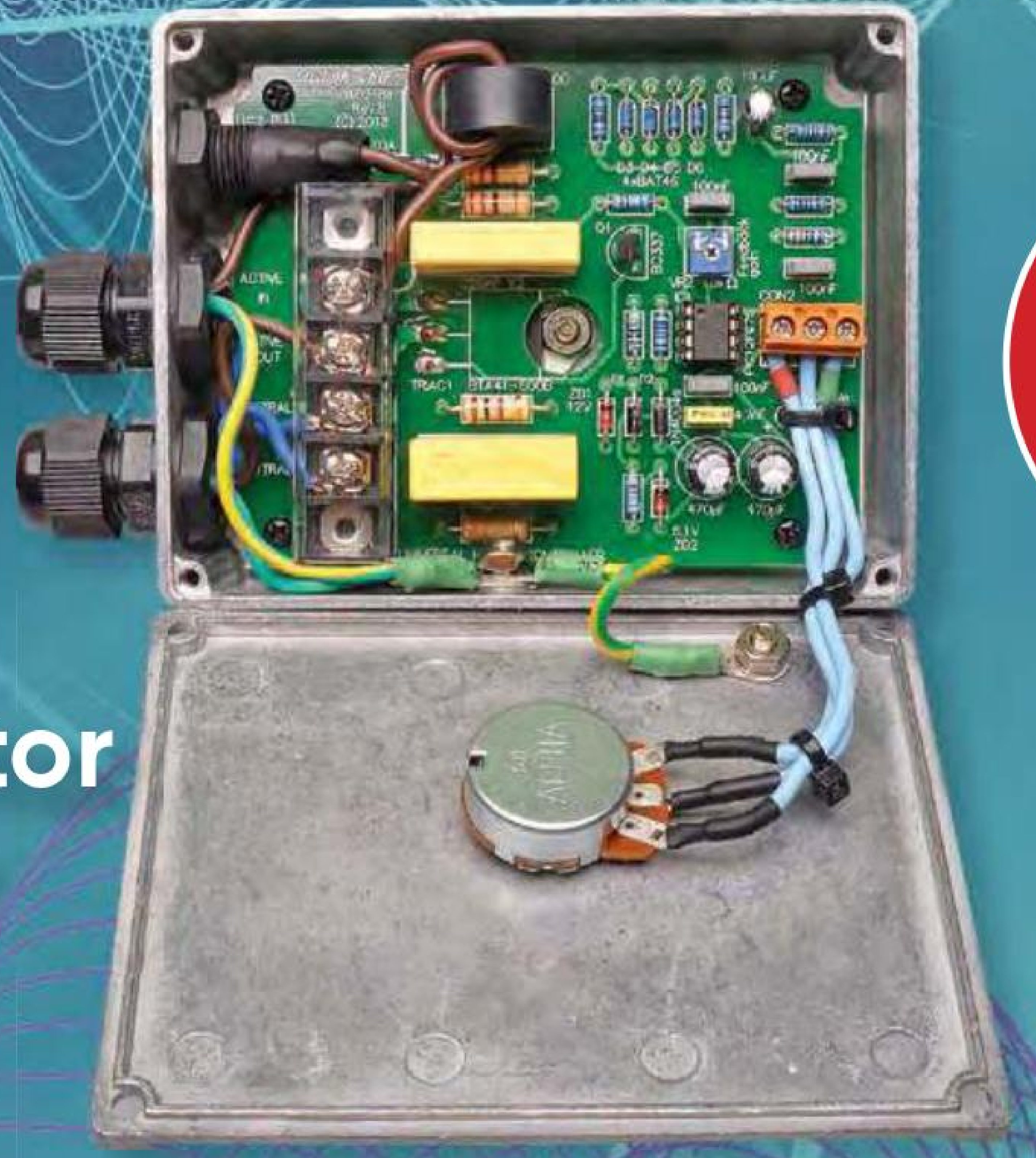

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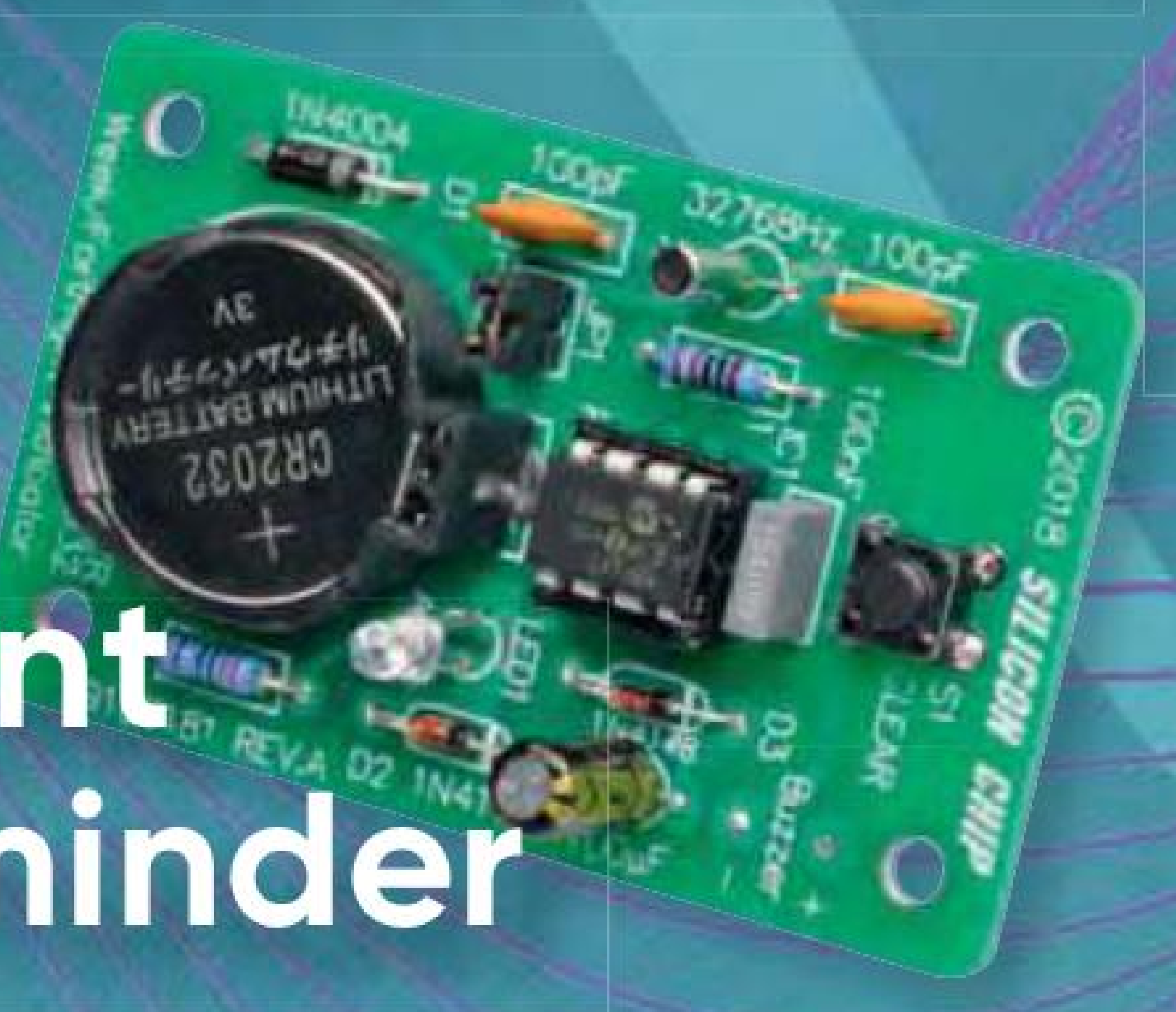

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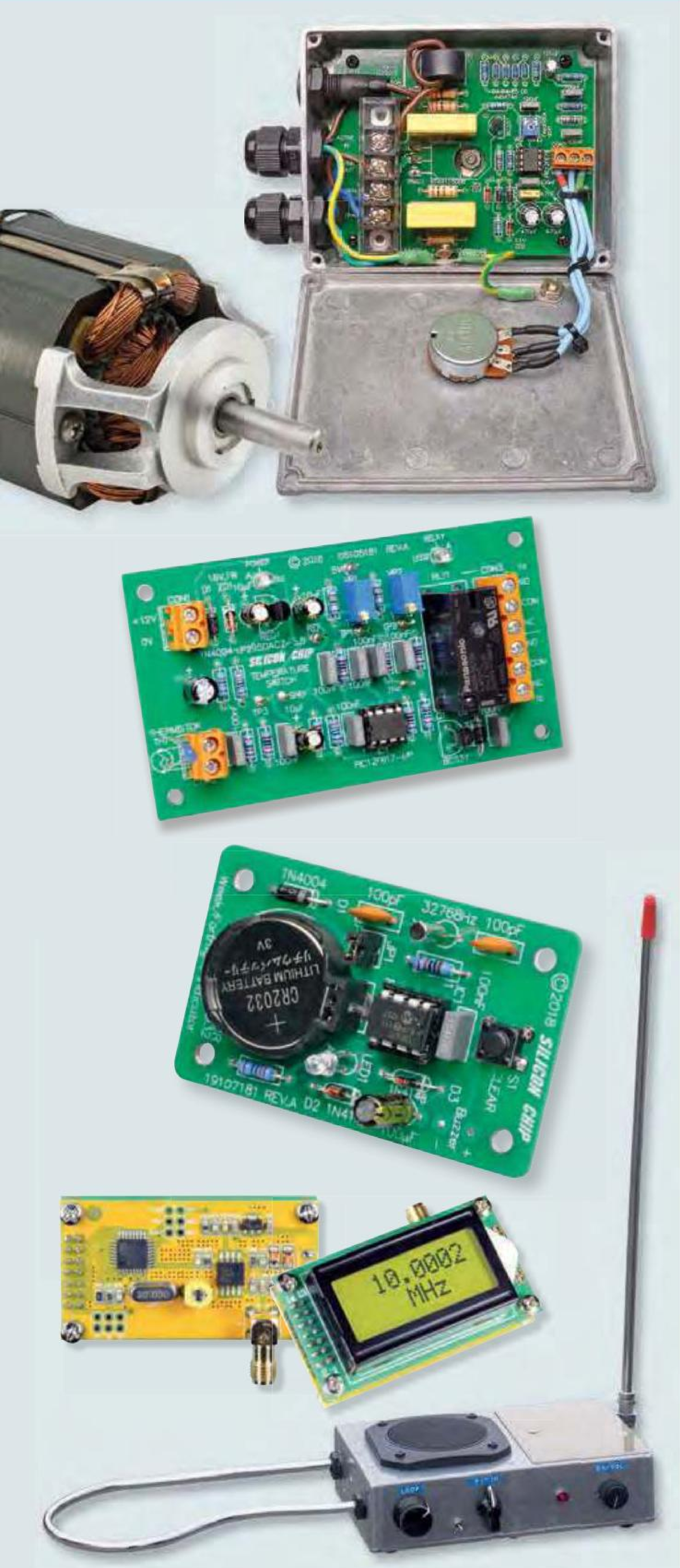
Practical
Electronics

Volume 48. No. 7
July 2019
ISSN 0262 3617

Contents



Projects and Circuits

Full-wave 10A Universal Motor Speed Controller by John Clarke 14
Highly effective triac-based circuit giving smooth, full-range speed control for electric drills, lawn edgers, saws or any appliance with universal motors rated to 10A.

Recurring Event Reminder by John Clarke 24
Bad memory? Forget to feed the pets every day? This simple circuit reminds you to perform regular tasks with a flashing LED or piezo siren.

Temperature Switch Mk2 by John Clarke 28
This very handy project with flexible switching lets you turn on a pump or fan if something is too hot... or turn on a heater if it's too cold.

Using Cheap Asian Electronic Modules – Part 18 by Jim Rowe 32
Learn to use a 500MHz frequency counter and associated wideband preamp.

MIDI Ultimate Synthesiser – Part 6 by Paul Cooper 36
In the last article of the series, final set-up and assembly into a bespoke case.

Series, Features and Columns

The Fox Report by Barry Fox 8
B&W audio meets mesh

Techno Talk by Mark Nelson 10
Fibre rage, more GPS spoofing and connectoritis

Net Work by Alan Winstanley 12
Networking around the house and the latest from Google Home

Teach-In 2019 – Powering Electronics by Mike Tooley 44
Part 8: Batteries

Circuit Surgery by Ian Bell 52
Understanding bipolar junction transistors – Part 1

Audio Out by Jake Rothman 55
The PE Theremin – Part 2

PIC n' MIX by Mike Hibbett 58
Small, cheap and powerful – Part 3

Max's Cool Beans by Max The Magnificent 62
Fixing BOB's dynamic range

Make it with Micromite by Phil Boyce 64
Part 6: Micromite-controlled Electronic Dice

Electronic Building Blocks by Julian Edgar 76
Spies alive!

Regulars and Services

Subscribe to Practical Electronics and save money 4
Practical Electronics back issues CD-ROM – great 15-year deal! 6
Reader services – Editorial and Advertising Departments 7
Editorial 7
Keep it simple
Teach-In bundle – what a bargain! 11
Exclusive Microchip reader offer 23
Win a Microchip SAM L21 Xplained Pro Evaluation Kit
Practical Electronics – get your back issues here! 69
Practical Electronics CD-ROMS for electronics 70
A superb range of CD-ROMs for hobbyists, students and engineers
Direct Book Service 73
Build your library of carefully chosen technical books
Practical Electronics PCB Service 78
PCBs for Practical Electronic projects
Advertiser index 79
Next month! – highlights of our next issue of Practical Electronics 80

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The August 2019 issue of *Practical Electronics* will be published on Thursday, 4 July 2019 – see page 80.

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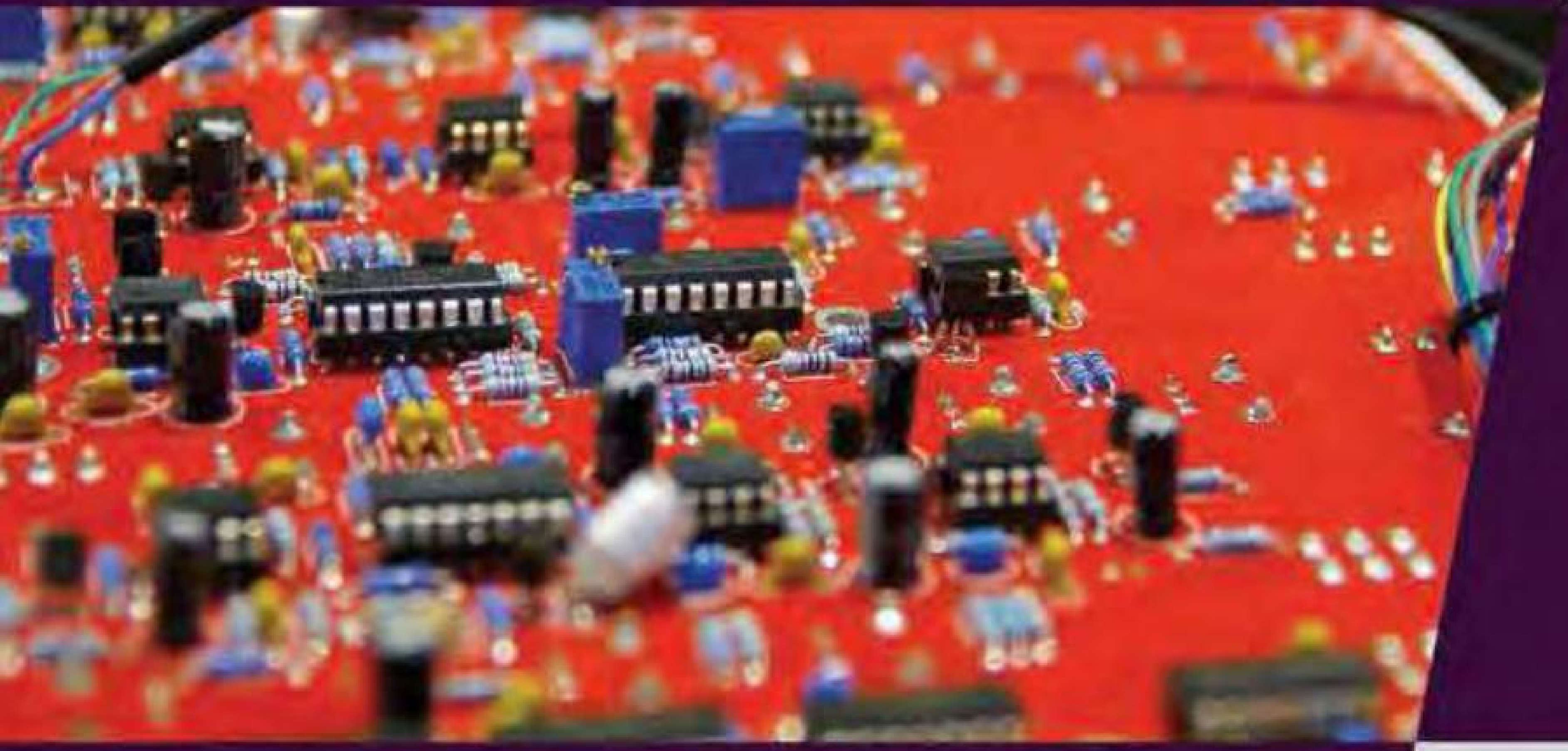

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Volume 48. No. 7
July 2019
ISSN 0262 3617

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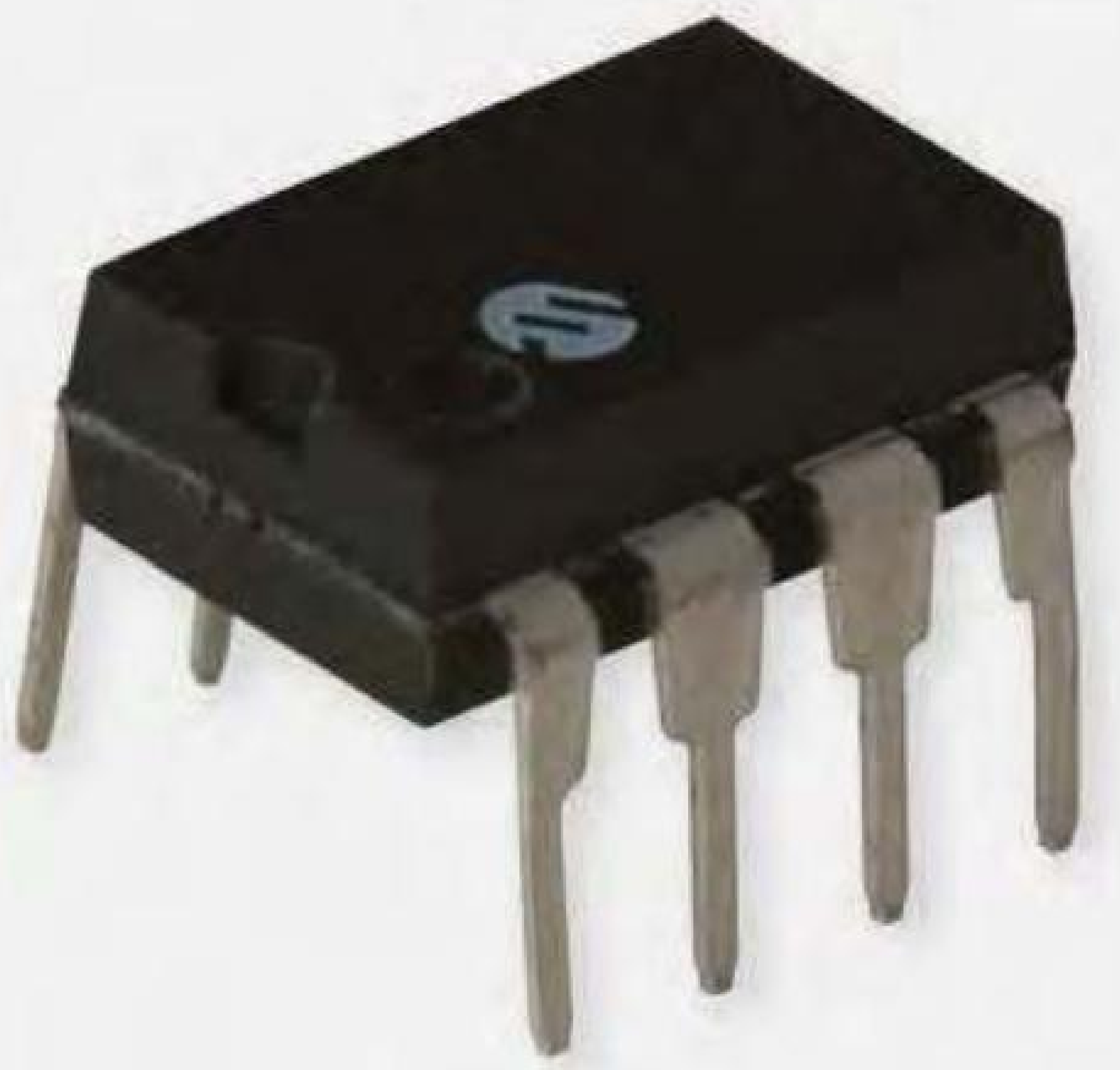

Keep it simple

A popular Internet meme reminds us that NASA got man to the moon with a computer boasting 64KB, but that we all need the latest 64GB smartphone to collect and upload selfies, tweets and other digital detritus. Perhaps a more grown-up version of this bloatware-shaming is the impressive fact that Microsoft's first and most 'basic' version of BASIC took up just 4KB of space – so small it was comfortably delivered on paper tape. (In comparison, the MS Word file for just this paragraph is 27kB.)

While one can take a minimalist design ethos too far – we all like a few bells and whistles in our projects – there is a lot to be said for not over-designing or reaching for a Raspberry Pi or Arduino every time we want to add a small amount of intelligence or decision-making-capability to a project. Yes, there are times when a pre-built single-board computer is entirely appropriate – last month's Arduino-based LC meter is a fine example – but often there are better, simpler routes.

We are currently running two excellent series that take different paths to this 'keep it simple' destination. Phil Boyce is now up to Part 6 in his *Make it with Micromite* series, and Mike Hibbett has just finished the first mini-project using one of Microchip's least complicated PIC microcontrollers – the humble PIC10F202.

Micromite offers users the simplicity of using just a few cheap components to take advantage of easy-to-write and intuitive BASIC programs – no complicated single-board computers needed; while the *PIC n' Mix* approach beautifully demonstrates the power of even the cheapest PIC and just a few dozen lines of code.

I hope you are enjoying these series and that you are inspired to implement these powerful, but inexpensive technologies into your own designs.

Matt Pulzer
Publisher

The **Fox** *Report*

Barry Fox's technology column

B&W audio meets mesh

Barry Fox auditions the new Formation range of mesh-technology wireless speakers from UK Hi-Fi icon Bowers & Wilkins. Despite some limitations, he is impressed with the overall product.

B&W's Formation range of wireless Hi-Fi speakers and audio connectivity products.

British company Bowers & Wilkins (B&W) has been making top end Hi-Fi speakers for more than 50 years. The company's first attempts at making wireless speakers were, to quote senior product manager, Steven Hoyle, 'hamstrung by lack of good wireless technology'. After a recent merger deal with Silicon Valley-based start-up EVA Automation, B&W has built its own wireless tech into the new Formation range of five speakers that each need only one cable – a mains lead. Formation uses Rune open-source software to aggregate all available digital musical services, such as NAS and USB storage, and Internet radio and streaming services, such as Spotify.

Mesh operation

Formation Wireless Technology uses the 'mesh' principle (sharing the same SSID and password round a home network) and works on standard Wi-Fi frequencies at 2.4 and 5GHz. But Formation is a closed, proprietary, wireless system. The upside is that everything works with simple setup, and the user only has to enter an SSID and password once. The mesh then shares it around. The downside is that there is no option to mix and match with other brand components. Fortunately, B&W makes some of the best speakers in the world (as used by studios like Abbey Road) and non-B&W hardware such as a vinyl turntable can be hooked into the Formation mesh by using the Formation Audio box, which turns any traditional analogue component into a high-fidelity streaming device.

So what exactly makes the Formation Wireless system different from more basic, and much cheaper, home network and streaming equipment?

Andy Kerr, director of product marketing, explains: 'Most wireless network and streaming systems use a single radio, which time-slices so that it can do everything it has to do, but it's continually hopping between different jobs. We use four completely separate radios, which all do different jobs.

'One radio works only with the home access point which is pulling in audio from the Internet. So it doesn't have to bother with other jobs, and fill up a buffer. The second radio is the in-room radio, which can synchronise all the speakers, including a subwoofer, with an accuracy of one microsecond – a millionth of a second. So everything is perfectly synchronised. And then

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we have a radio that is controlling the room-to-room connection of speakers. The fourth radio is for Bluetooth. So there is complete separation of the tasks. That's what makes Formation fundamentally different from other wireless systems on the market'.

Because there is no time-slicing and workload sharing, the Formation can work with uncompressed 24-bit/96kHz resolution audio. The microsecond syncing means that sound between speakers and rooms is tightly locked together without any audible delays.

Bluetooth use

I asked B&W what the Bluetooth radio does. They explained that Bluetooth is used to get music into the system, from a transmitting device such as a phone that is being used as a music store. But once music content is inside the system, it is then retransmitted between speakers and spaces using the Wi-Fi 96kHz/24-bit Formation Wireless Mesh network – not Bluetooth. The mesh uses uncompressed PCM.

Formation supports Bluetooth aptX HD coding, which uses moderate compression to handle up to 48kHz/24-bit coding; but only if aptX is supported by the transmitting device, of course. Where aptX HD is not supported by a phone or other music source, the Formation system will default to other, lower-quality forms of Bluetooth audio.

Voice control and HDMI?

Formation does not offer voice control. Says Steven Hoyle: 'The first question we would have to ask and answer would be, which system should we back (eg, Amazon Alexa, Apple Siri or Google Assistant). And these speakers play loud, so there are inevitably problems with them hearing voice commands.'

One of the Formation products is a high-end sound bar for use with a TV. Because of the microsecond time accuracy there is no problem over lip-syncing speech and vision. But surprisingly, the Formation Bar does not have an HDMI connector. B&W says, rather unconvincingly, that this is because the design was originally for the US market, where S/PDIF optical connectors are favoured. But this should change with the new HDMI standard for Enhanced Audio Return Channel connection, which lets an HDMI cable carry high-resolution multi-channel sound both ways between a sound bar and TV.

Control

In the meantime, the Formation Bar plays the clever trick pioneered by German speaker company Canton; the bar box 'learns' the basic audio control commands used by the remote control for the connected TV. So the TV remote also controls the sound bar volume.

Prices for the Formation range are high but, on the strength of recent demonstrations given in London, justifiable for anyone prepared to pay for the uncommon combination of style, convenience and high-quality wireless audio.

Range overview

The Formation Wedge is an elliptical stereo speaker that looks like a large and stylish rugger ball, and costs £899.99; Formation Bar is a TV sound bar with nine drive units, including hard-centre source, costing £999.99; Formation Bass pairs with other Formation components to enhance bass reproduction and costs £899.99; Formation Duo speakers are wireless versions of B&Ws wired units, costing £3,499.99, plus £699.99 for matching stands; and Formation Audio uses a high quality ADC to stream analogue audio into the wireless mesh at a price of £599.99.

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Marconi 2955B Radio
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Fibre rage, more GPS spoofing and connectoritis

Techno Talk

Mark Nelson

If that sounds like an odd mixture, you're not wrong. But you weren't expecting anything conventional, were you? So, carry on reading to have your mind stretched…

We begin with a paradox concerning the roll-out of fibre broadband. Although the government trumpets the manifold advantages and benefits of running fibre all the way into our homes, offices, schools, hospitals and factories, some doubts remain. The most obvious concerns are how long we must wait for it to be rolled out, how much extra we shall have to pay and whether it will ever reach remote villages and farms. A less obvious question is whether people who have no desire for broadband and want only a low-cost basic telephone service will be transferred to a new fibre 'telephone line' at a cost no greater than what they pay currently. To put the cat among the pigeons, there's a contention that fibre may never reach the most far-flung locations, because it will be cheaper to provide connectivity by new 5G cellular radio services – if these are delivered on schedule.

One thing not widely discussed is how 999 (UK emergency) calls will be affected by the changeover to fibre. Currently, these communications travel over conventional copper cable, whose metallic conductivity enables telephones to be powered by substantial 50V batteries located at the telephone exchange, meaning that even if the mains supply to your premises fails, you can still expect your telephone to work. Once we change to optical communication, we lose that convenient 50V power source, meaning that your existing telephone will cease working. As likely as not, your phone company will provide an analogue terminal adapter (ATA) into which you plug your old phone, but this ATA will rely on mains power to operate. Any power cut will not only put your broadband out of action but also your phone. Many people will have a mobile phone, but emergency calls made from a mobile take significantly longer to connect for reasons too technical to explain here.

Only in America

In the US, subscribers are already reaping a whirlwind of unplanned side effects of the fibre changeover. In many areas, telephone and broadband users have been forcibly migrated to fibre service and some of them are not happy at all. For example, one says: 'My service provider, Verizon, wanted to cable the apartment block where I live for fibre, so I tried to persuade my landlord to let them install fibre. Ultimately, he said 'no' because his old run-down apartment building is beautiful and perfect, and the phone company would surely destroy it during their installation. I reported this to Verizon, who told me that if my landlord would not let them come in to install fibre, my service would be terminated.' Following similar incidents, there is now a 'Save Landlines' organisation that deals with exactly this type of activity on a daily basis (information at: **http://landlines.ml/act/** and **https://savelandlines.org**).

Untrustworthy GPS confirmed

In *Techno Talk* for December 2017 we mentioned speculation that Russia might be testing a new system for spoofing GPS that could lead to new forms of electronic warfare. It now transpires that Russia is now faking GPS signals on an industrial scale. A report by C4ADS, a non-profit organisation providing evidence-based reporting on global conflict and transnational security issues, has revealed findings from a year-long investigation on the use of GPS tampering. It asserts that these attacks are emerging as a viable, disruptive strategic threat – and are much larger in scope, more diverse in geography, and longer in duration than any public reporting suggests to date.

This activity is directed toward three entirely separate applications. The first of these is protection of very important persons (VIPs). C4ADS found a close correlation between movements of the Russian head of state and GPS spoofing events. It believes the Russian Federal Protective Service (FSO) operates mobile systems to support this activity. The report also profiles the use of Russian GPS spoofing for strategic facilities protection in Moscow and protected locations on the coast of Russia and Crimea in the Black Sea. The report's third exposure concerns a capability scarcely reported in the public domain. This is the use of GPS spoofing in active Russian combat zones, particularly Syria, for airspace denial purposes. Using data from a scientific sensor on the International Space Station (ISS), C4ADS was able to identify ongoing activity that poses significant threats to civilian airline GPS systems in the region.

A secret obsession – connectoritis

Judging by spirited discussions in Internet forums (or *fora*, if you prefer), I'm not the only one fascinated by electronic plugs and sockets, as you would know if you read (and remember) *Techno Talk* for August 2014. That article covered the origins and inventors of UHF, N, C, BNC and TNC connectors. One pattern of connector we did not examine was the F-type that is used on systems as diverse as cable broadband, satellite receivers and some scanner radios. It transpires that this exemplar of cheap and cheerful 'value engineering' is the invention of Eric Winston in or around the year 1950 while working for Jerrold Electronics in the US on their development of cable television. Like the earlier and slightly smaller C-type (not to be confused with Concelman's C-type used in professional and military antenna installations), the plug has no centre pin, using the solid centre wire of the cable instead.

This has always struck me as a weak point, as is the use of a base-metal signal conductor directly inserted into the socket. Even with precious metal on the female socket contact side, there is bound to be corrosion on the signal conductor of the lead over a long time. The cheaper types are far from waterproof. According to some people, the F stands for 'ferrule'(photos at **http://bit.ly/pe-jul19-catv**). Finally, **www.alfarconnectors.com/f-fme-connectors/** is a useful page that explains that the F connector is for 75Ω cable, while the similar FME (= F for mobile equipment) connector is for 50Ω cable. So now you know!

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Net Work

Alan Winstanley

This month, *Net Work* revisits networking around the house, covers the latest hardware and software for Google's Home range of products and reports on a not-so-smart AI algorithm.

Last month, I highlighted some options available to Internet users seeking to extend Wi-Fi coverage around the home. Choices include standalone plug-in wireless extenders, 'whole home' wireless mesh or HomePlug-type power-line communications (PLC) systems such as Devolo's popular dLAN 500 family. This can provide both LAN (Ethernet ports) and Wi-Fi by utilising a building's mains electrical circuit to carry high-frequency signals. Connect one adaptor to a nearby router, then plug in PLC adaptors around the home and let the electrical ring main(s) take care of the rest – in theory, anyway, but more about that, later! Note that in last month's column I said that powerline devices need to share the same AC electrical phase: Devolo states that their dLAN products will operate successfully when powered on multiple (parallel) phases.

One relatively costly option to extend Wi-Fi around the home is to invest in a 'Whole Home' mesh system such as the Alexa-aware Linksys Velop, TP-Link Deco, Google Wi-Fi, British Telecom's Whole Home Wi-Fi or Amazon's forthcoming mesh system. These products aim to offer wireless coverage throughout the property, automatically selecting the most reliable 'internal' route to carry traffic. As older network hardware is gradually retired, mesh networking is probably the way that home connectivity will go.

Prosumer users wishing to stream VR or HD video wirelessly over their home network might consider Devolo's 'Magic 2' range, which currently claims to be the world's fastest powerline-type adaptor at 2.4 Gbps (theoretical maximum); Devolo also claims to be the first in this market to use the high-speed G.*hn* protocol that has tantalised the network telecoms industry for the past ten years. North American manufacturer Comtrend, a brand not sold in Europe, grabbed this prize for themselves though, by launching the first G.*hn* PLC adaptor back in 2014, they say, and have had a 2 Gbps version in the pipeline since last year. With the exception of TP-Link's new TL-WPA9610 AV2000 kit, other brands of 2 Gbps (2000 Mbps) powerline products seem virtually non-existent at the present time, leaving buyers with a choice of cheaper 1200 or 500 Mbps equipment instead.

APC powerline-compatible power strip, available with UK and continental sockets.

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About Schuko
Company

The Google Nest Hub smart speaker has a 7-inch LCD touchscreen. The new 10-inch Nest Hub Max arrives soon.

Powerline pitfalls

Manufacturers' data transfer rates are optimistic theoretical 'up to' values under optimal conditions. Devolo adds that its Magic 2 will enable 8K video to be streamed around the home network, but speed may be affected if other types of PLC devices are used on the same ring main and, naturally, its G.*hn* technology does not support older dLAN adaptors. Devolo's lower-priced Magic 1 range claims theoretical speeds of 1.2Gbps.

Powerline communication networks have a topology all of their own and results in practice may be far from ideal. To fill a Wi-Fi 'dead spot' in a room the author added a Devolo dLAN 500 adaptor which cured a PC connectivity problem satisfactorily. However, the quality of electrical wiring, the presence of suppressors, extension leads, uninterruptible power supplies, poor or 'noisy' connections and interference from other appliances can all degrade performance. Connecting a powerline product to any of them can slow or block transmissions altogether, says Netgear, as they can filter out the high frequency signals that PLCs depend on. Power product manufacturer APC markets a mains extension lead (power strip) with PLC applications in mind – for example, the APC PL5B Essential SurgeArrest five-outlet surge-arrestor has reduced filtering on one outlet and is labelled as 'powerline compatible', so you could connect a HomePlug adaptor to it. Both 5-way and 8-way power strips are sold. The photo shows UK-style sockets, but Schuko-type mains outlets are also available (**http://bit.ly/pe-jul19-apc**).

Nesting at Home with Google

Regular readers might recall that I recently acquired a clutch of Google Home Mini Wi-Fi smart speakers, handy puck-sized gadgets offering hands-free interaction with Google Assistant. They've proved useful for reading out news headlines, setting alarms, reminders, broadcasting quick messages around the house (Dinner's ready!, Time for bed!), listening to schedules, 'googling' whether a certain shop is still open, or acting as a spell-checker, unit converter, calculator or dictionary. Home Minis can also help less able-bodied users by speaking the time or date, tuning in to a streaming radio station, and when used with smart IoT adaptors, simple voice commands can help with practical tasks such as switching on lights or electrical appliances.

Google Home's voice recognition capabilities are second to none and it also has a powerful language translation function that can surprise and delight: over breakfast, while musing over some toast and marmalade the author decided to practise his rusty Spanish and asked a nearby Home Mini to translate the label on the Seville marmalade: 'Hey Google, translate 'La Vieja Fabrica', and after repeating the phrase back to me in an authentic Spanish dialect it gave the answer, 'It means the old factory in Spanish'. Google Translate is a good learning aid that's fun to use, but as data is derived from the web at large, some limitations and inconsistencies soon become evident.

Hey Google

One aspect that rankles a bit is the need to precede each command with 'Hey Google' or 'OK Google', so Google has introduced a 'continued conversation' feature that keeps the dialogue open, giving you time to add a supplementary question or command. It can be enabled in the Google Home app on your phone or tablet: go to: Account/ Settings/ Assistant tab/ Continued Conversation. Your Google gadget will re-open the microphone, allowing follow-up time without having to say 'OK Google' again. Continued conversation is currently an English-only feature, and remember that these features can also be used with Android phones.

In May, Google rebranded its Home Hub LCD smart speaker as the 'Nest Hub' and so, buoyed by positive experiences of the Home Mini, one arrived on the doorstep just twelve hours after ordering it online. These unobtrusive 'dumb tablets' are available in four colours and sit neatly on a desk, bookshelf or table top. They are initialised using the Google Home app using a smartphone, and after detecting the newly enlarged Devolo-based Wi-Fi network the author's Nest Hub automatically downloaded an update and then the fun began.

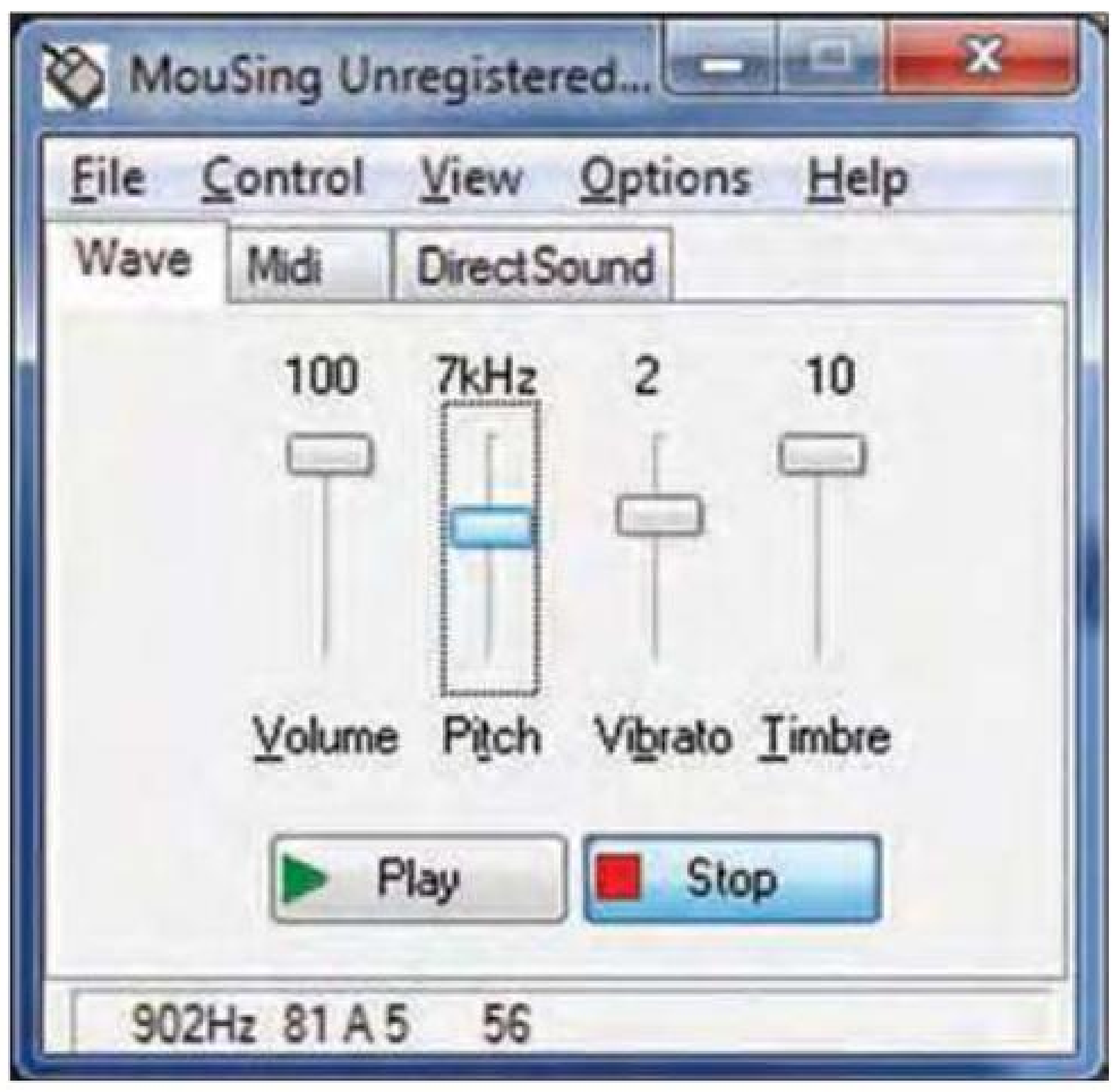
The Nest Hub's 7-inch touch-sensitive colour display is clear and has a good viewing angle. Its voice recognition works extremely well, with the added bonus that spoken commands are recognised and appear on-screen as a useful confirmation. The built-in microphone can be switched off manually, noting that this version of the Nest Hub has no camera. In between times it can act as a clock or a photo frame, streaming images from the user's Google Photos gallery. Its 'Ambient EQ' feature, when enabled, analyses the room's ambient colour and light levels, and chooses photos that best blend into the surroundings as well as automatically dimming, or blanking the display altogether when appropriate (eg, night time by the bedside).

Toil and trouble...

One of Google Home's handy features is its ability to read out the latest news bulletins, in the writer's case streaming from the UK-based BBC and Sky News. (Amazon's Alexa does the same.) After setting the Nest Hub in-situ on a desk though, some network shortcomings were soon discovered; it would hesitate or stall when trying to stream Sky News video bulletins, presumably due to poor bandwidth or Wi-Fi connectivity. Google Assistant responded to voice commands as expected but, disappointingly, video clips or YouTube video stuttered and stopped, and viewing them on the Nest Hub was impossible. This showed how hit-and-miss powerline networking can be. The solution was to move the Nest Hub onto the router's Wi-Fi network instead, since the router was only three feet away under the desk! Then the smartphone hosting the Google Home app has to switch to the Nest Hub's native SSID to finish setting up, after which the Nest Hub sprang into life and Sky News and YouTube streamed smoothly onto its screen as expected.

The usual Google search features are on tap and the Nest Hub becomes one of those things that you keep finding uses for. For example, I could ask it to show me a picture of a Schuko mains connector just to make sure – it correctly recognised and spelled 'Schuko'. Screens can be 'swiped' in the traditional tablet manner but I found its limited navigation generally less easy or intuitive than the desktop or tablet versions. A YouTube news clip of a UK Parliament debate could easily be cast from my smartphone onto its display or a Chromecast-equipped TV instead. Overall, network bottlenecks aside, the 'Google Assistant' way of doing things hangs together very well and brings some worthwhile benefits to a busy household or desk. The flip side has been an increased monthly broadband fee due to a tariff-busting leap in data usage!

Google has also announced a new Nest Hub Max with 10-inch HD display, stereo 2.1 speakers and built-in camera for security monitoring and video calls. They're on pre-order at £219 (UK) or $229 (US).



Sagebrush Systems' MouSing Theremin simulator is an old *Net Work* favourite.

One potato, two potato

A quick round-up to finish this month: it's always a pleasure to read Jake Rothman's latest endeavours in our *Audio Out* column and the latest *PE Theremin* will doubtless spark a lot of interest amongst electronic music enthusiasts. For anyone wanting to sample the Theremin experience, a quick search on my hard disk highlighted *Net Work*, July 1997, when I mentioned a Windows Theremin Simulator called MouSing sold by the small developer Sagebrush Systems. Happily, this old *Net Work* favourite is still available from **https://sagebrush.com/mousing** for a modest cost (free demo available) and it has some MIDI capabilities too. It also works with a graphics tablet. A number of other Sagebrush Windows and Android apps are worth browsing through at the same time.

Satellite comms company OneWeb (see *Net Work*, *PE*, May 2019) aims to launch 600 satellites intended to provide Internet access to remote places around the world but this may be dwarfed by Amazon who are now recruiting engineers to work on its Project Kuiper, a constellation of no less than 3,200 satellites aiming to 'offer high-speed broadband connectivity to unserved and underserved communities around the world.' See: **http://bit.ly/pe-jul19-kui**

Tunnel borer, sir?

Finally, we know how Internet sellers' 'AI' systems try to figure out our interests so they can target more products at us, but I wonder what the Chinese vendor Alibaba must think of me after I bought a solitary OLED display from Asia. Alibaba's latest email shot suggests I might be interested in an 800cc motorbike, a tunnel boring machine costing $½m or maybe some Vietnamese potatoes! See you next month for more *Net Work*.

The author can be reached at:
alan@epemag.net

Triac based for ultra-smooth control!

Full-wave 10A Universal Motor Speed Controller

BY JOHN CLARKE

This relatively simple but highly effective triac-based circuit gives smooth, full-range speed control for electric drills, lawn edgers, circular saws, routers or any other appliance with universal motors (brush type), rated up to 10A.

Most SCR or triac-based speed controllers usually have very poor low-speed control and won't let the motor reach full speed. This speed limitation comes about because these circuits can only switch on every second half-wave of the 230VAC mains voltage. This means that they can only feed a maximum voltage of about 160VAC to the motor.

These limitations are demonstrated in the waveforms shown in Scope1 and Scope2, which come from a 10-year-old half-wave speed controller.

Up till now it has been very difficult to design a triac-based circuit which would give smooth control over a wide range of speeds.

Nor was it is easy to provide good speed regulation, which means that the motor speed is less likely to vary if the loading changes.

But our new *Full-wave Universal Motor Speed Controller* provides much improved speed control because it not only uses a microcontroller to provide more precise phase control of the triac, but also it employs current feedback.

This is not our first full-range speed control for universal motors. Our last design was featured in the March and April 2015 issues of *EPE*.

This had a complex circuit that rectified the 230VAC mains and used a rugged IGBT (insulated gate bipolar transistor) to rapidly switch the pulsating DC waveform at 980Hz.

At low speeds, very narrow pulses are applied to the motor while at full speed the IGBT is continually on. This technique is referred to as 'pulse-width modulation' (PWM).

That design is still valid, but due to its complexity, it also meant that it was (and still is) large and expensive.

Our new triac-based design also offers impressive performance but it is less complex and less costly. The triac is phase controlled and works similarly to a leading-edge light dimmer (more on phase control later).

The 600V 40A triac is also arguably more rugged than the IGBT used in the 2015 design.

Soft start

A particularly attractive feature of this new design is 'soft start'. This means that regardless of speed setting, the motor speed will smoothly build up to the setting and thereby avoid any sudden kicks – an all-too-common reason for users presenting at hospital casualty rooms!

The new *Speed Controller* can be used with a 220V to 250VAC mains supply, at 50Hz or 60Hz. This means that it can be used in any country that has a 220VAC supply or above. However, it is not directly suitable for use with a 110VAC mains supply; that would required some component changes.

Why do you need speed control?

Most power tools will do a better job if they have a speed control. For example, electric drills should be slowed down when using larger drill bits. This is particularly the case when drilling sheet metal; using too fast a speed will result in a triangular hole.

Similarly, it is useful to be able to slow down routers, jigsaws and even circular saws when cutting some materials, particularly plastics, because many plastics will melt rather than be cut if the speed is too high.

The same comments apply to sanding and polishing tools and even electric lawn trimmers, where they are less likely to snap their lines when slowed down.

Features

- **Full-wave motor control**
- **Full speed range**
- **220VAC to 250VAC 50Hz/60Hz**
- **For 'universal' motors (ie, series motors with brushes)**
- **10A 230VAC or similar nameplate rating**
- **Soft start**

Even if you do not want a reduced motor speed, the soft start feature of this *Speed Controller* is handy when using large power tools such as circular saws and routers, which can give a substantial kick if started at full voltage. (Some modern power tools, such as electric chainsaws, have this feature built-in).

Phase control

Before we continue, we should explain what we mean by 'phase controll' – the technique used in this new design.

As you know, the mains AC voltage is a sinewave. It starts at zero, rises to a peak, falls back to zero, then does the same thing with the opposite polarity. This repeats 50 times each second for 50Hz mains and 60 times per second for 60Hz mains.

We vary the speed of a motor by varying the time during each half cycle when power is applied: feed power very early in the cycle and it runs fast; delay applying power until much later in the cycle and it runs slowly.

Phase control employs either an SCR (silicon-controlled rectifier) for half-wave control or a triac to provide full-wave control, as used in 'leading edge' dimmers.

Half-wave control means that only one side of the mains waveform (the positive or the negative) is applied to the motor.

These devices are turned on by a trigger pulse applied to their gate electrodes and the term 'phase control' comes about because the timing of the trigger pulses is varied with respect to the phase of the mains sinewave.

Speed regulation

For a motor to have good low-speed performance, the speed control circuit should compensate for any drop in motor speed as the load increases, by increasing power to the motor. Many simple SCR speed controllers rely upon the fact that a motor produces a back-EMF (electromotive force) which is proportional to its speed.

The circuit compensates for a drop in back-EMF by triggering the SCR earlier in the mains half-cycle and so applying more voltage to the motor.

In practice, the back-EMF generated by most appliance motors is quite weak while the SCR is not conducting. This is partly because there is no field current and the generation of voltage is only due to remnant magnetism in the motor core.

Furthermore, any back-EMF that is produced tends to be too late after the end of each half-cycle to have a worthwhile effect on the circuit triggering in the next half-cycle.

Our new *Speed Controller* uses a different method to provide good speed regulation. It monitors the motor current to sense motor speed. If it senses a drop in speed, it increases the effective voltage to the motor.

This new design uses the triac to apply AC to the motor and it is triggered in both half-cycles of the mains waveform. Unfortunately, the triggering requirements for correct operation with an inductive load such as a motor cannot be provided by a simple circuit. In fact, the triac must have multiple triggering pulses in each half-cycle and their timing is very critical. The only solution is to use a microcontroller. So let's have a look at the full circuit in Fig.1.

Circuit description

The key components are the triac and the PIC12F675 microcontroller, IC1. IC1 monitors the speed potentiometer, VR1 at pin 6. It also monitors feedback gain potentiometer VR2, at pin 3, the current feedback via current transformer T1, at pin 7 and the mains waveform via a 330kΩ resistor at pin 5.

SILICON CHIP
Full Wave 10A
Motor Speed Controller
for universal motors
10A
Fuse
Nameplate rating
up to 10A, 230VAC
50Hz or 60Hz
Not Suitable for
induction motors
SPEED
www.siliconchip.com.au

In response to all those parameters, IC1 produces a series of pulses and these drive NPN transistor Q1 and then the gate of the triac.

The triac gate current flows via the 47Ω resistor connected between the 5.1V supply and the triac's A1 terminal, then out through the gate and to circuit ground via Q1 (ie, the gate current is negative).

This method of connection places the 47Ω resistor between the 230VAC mains supply and the 5.1V supply which runs the PIC microcontroller. This arrangement has been used to avoid triac switching noise getting into the 5.1V supply, which can cause latch-up of the microcontroller.

Snubber network

A snubber network comprising two 220Ω 1W resistors in series and a 220nF 275VAC X2-rated capacitor is connected between the A1 and A2 terminals of the triac. This network is there to avoid rapid changes in voltage being applied to the triac which would otherwise turn it on (dV/dt switching) when it is supposed to be off.

These rapid changes in voltage can occur then power is first applied or can come from voltage transients generated by the inductance of the motor being controlled, each time the triac turns off. In effect, the snubber network acts to damp transients and reduce their amplitude.

The DC supply for the microcontroller is derived directly from the 230VAC mains supply via a 470nF 275VAC X2-rated capacitor in series with a 1kΩ 1W resistor. The capacitor's impedance limits the average current drawn from the mains, while the 1kΩ resistor limits the surge current when power is first applied.

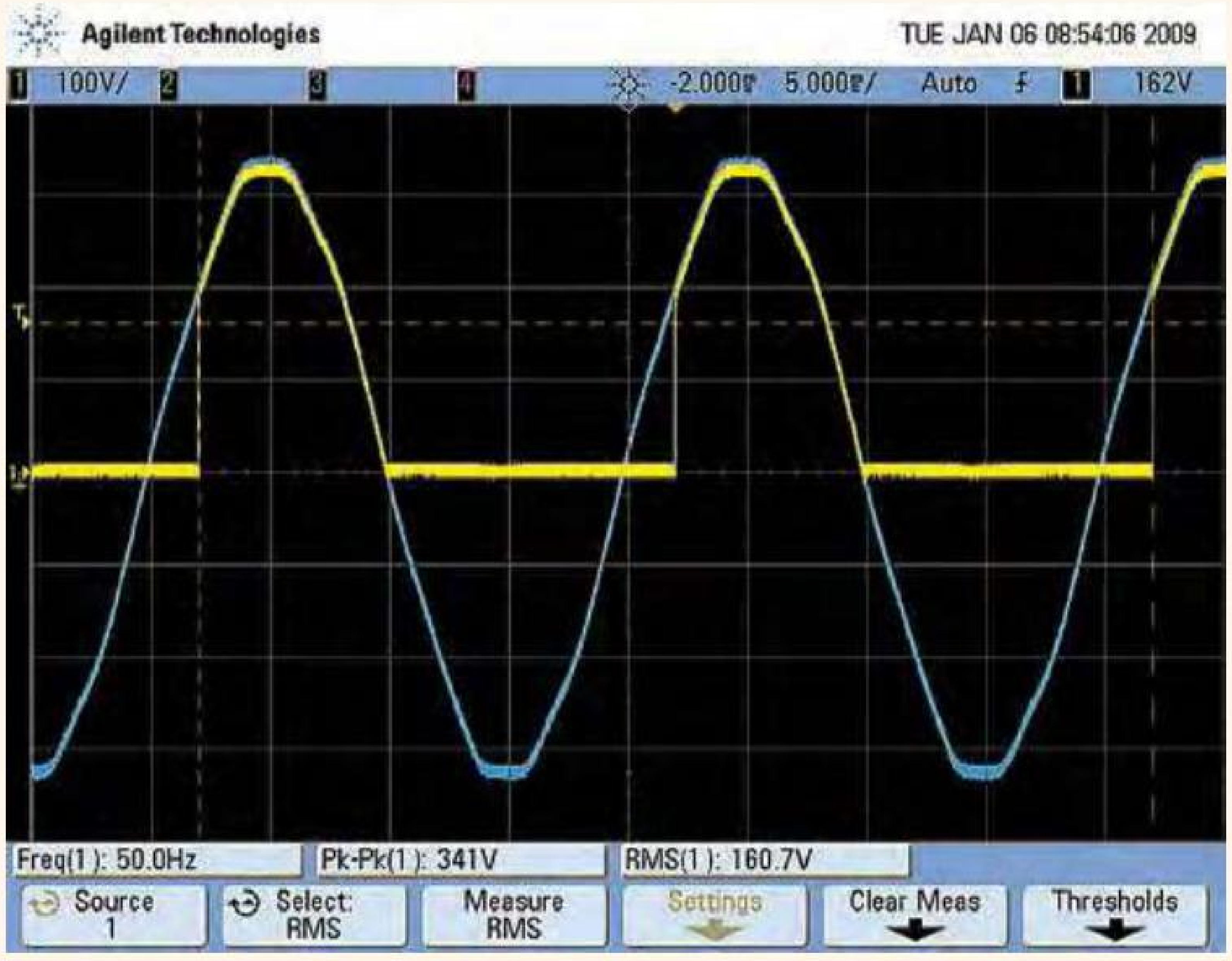
It works in the following way. When the neutral line is positive with respect to the live line, current flows via the 470nF capacitor and diode D1 to the 470µF capacitor to charge it up. On negative half-cycles, the current through the 470nF capacitor is reversed via diode D2.

Zener diode ZD1 limits the voltage across the 470µF capacitor to 12V and that supply then feeds a second 470µF capacitor via a 47Ω resistor and its voltage is limited to 5.1V by zener diode ZD2. This is the supply for the microcontroller, IC1.

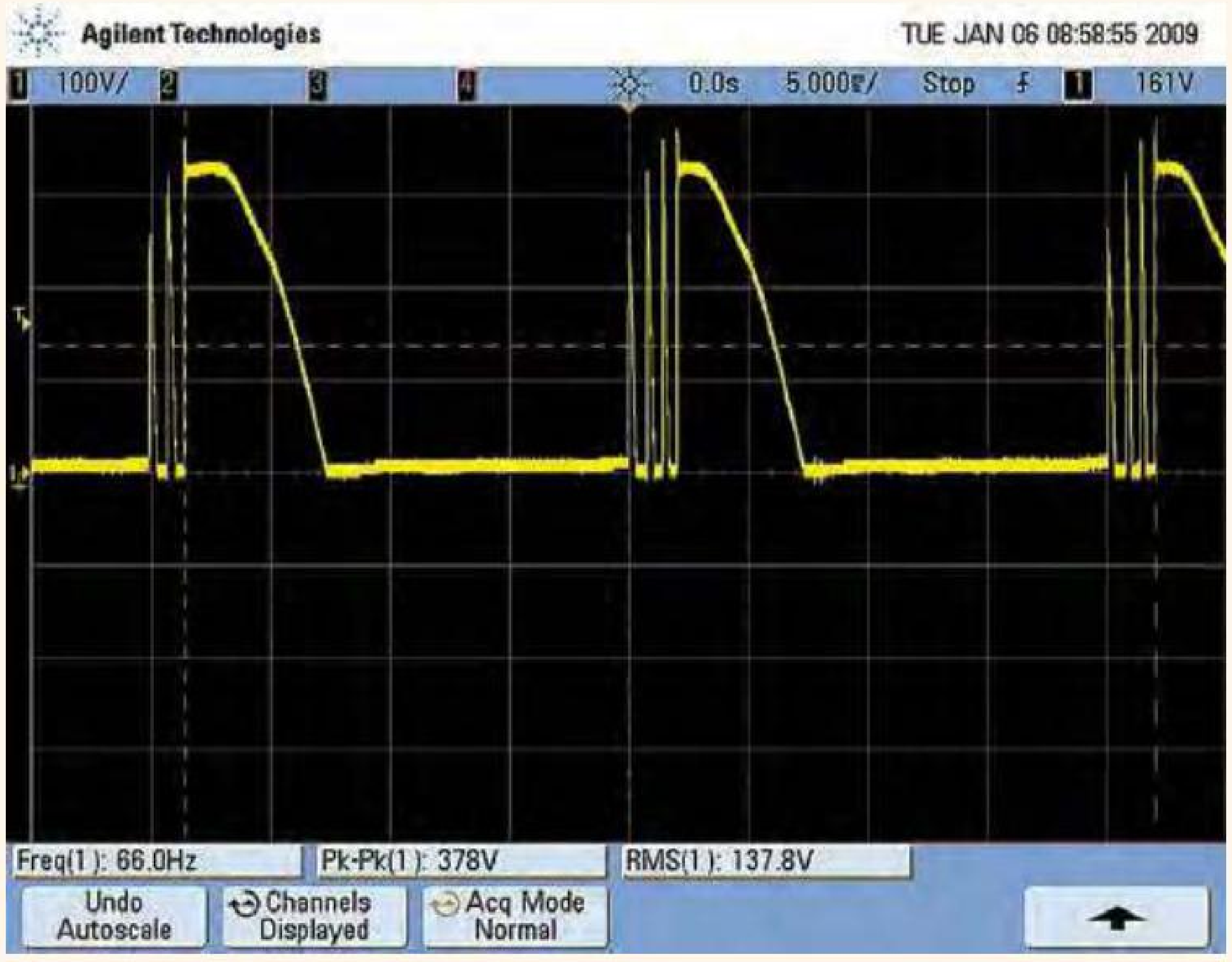
IC1 has its $\overline{\text{MCLR}}$ input (pin 4) tied to the 5.1V supply via a 10kΩ resistor and this provides a master clear (reset) for IC1 when power is applied. The main 5.1V supply for IC1 is decoupled with a 100nF capacitor.

VR1 is the speed potentiometer and it is connected across the 5.1V supply with the wiper connected to the pin 6, AN1 input. IC1 converts the voltage set by VR1 into a digital value using its internal analogue-to-digital converter (ADC). The 100kΩ resistor from the wiper to ground holds the AN1

These half-wave control waveforms are taken from our February 2009 Drill Speed Controller, for comparison with the new one . . .


Agilent Technologies
TUE JAN 06 08:54:06 2009
1 100V/ 2 3 4 -2.000ſ 5.000ſ/ Auto f 1 162V
Freq(1): 50.0Hz
Pk-Pk(1): 341V
RMS(1): 160.7V
Source 1
Select: RMS
Measure RMS
Settings
Clear Meas
Thresholds

Scope1: the controller is set for maximum output with resistive load. The yellow waveform is essentially a half-wave rectified sinewave with a value of 161V RMS (70% of the blue 230V mains waveform) and a peak value of 341V.


Agilent Technologies
TUE JAN 06 08:58:55 2009
1 100V/ 2 3 4 0.0s 5.000ſ/ Stop f 1 161V
Freq(1): 66.0Hz
Pk-Pk(1): 378V
RMS(1): 137.8V
Undo Autoscale
Channels Displayed
Acq Mode Normal

Scope2: the Speed Controller set for maximum output when driving an electric drill. There is considerable hash at the beginning of each positive half-cycle, caused by interaction between the drill's commutator and the triac.

input at 0V, setting motor speed to zero should VR1's wiper go open-circuit.

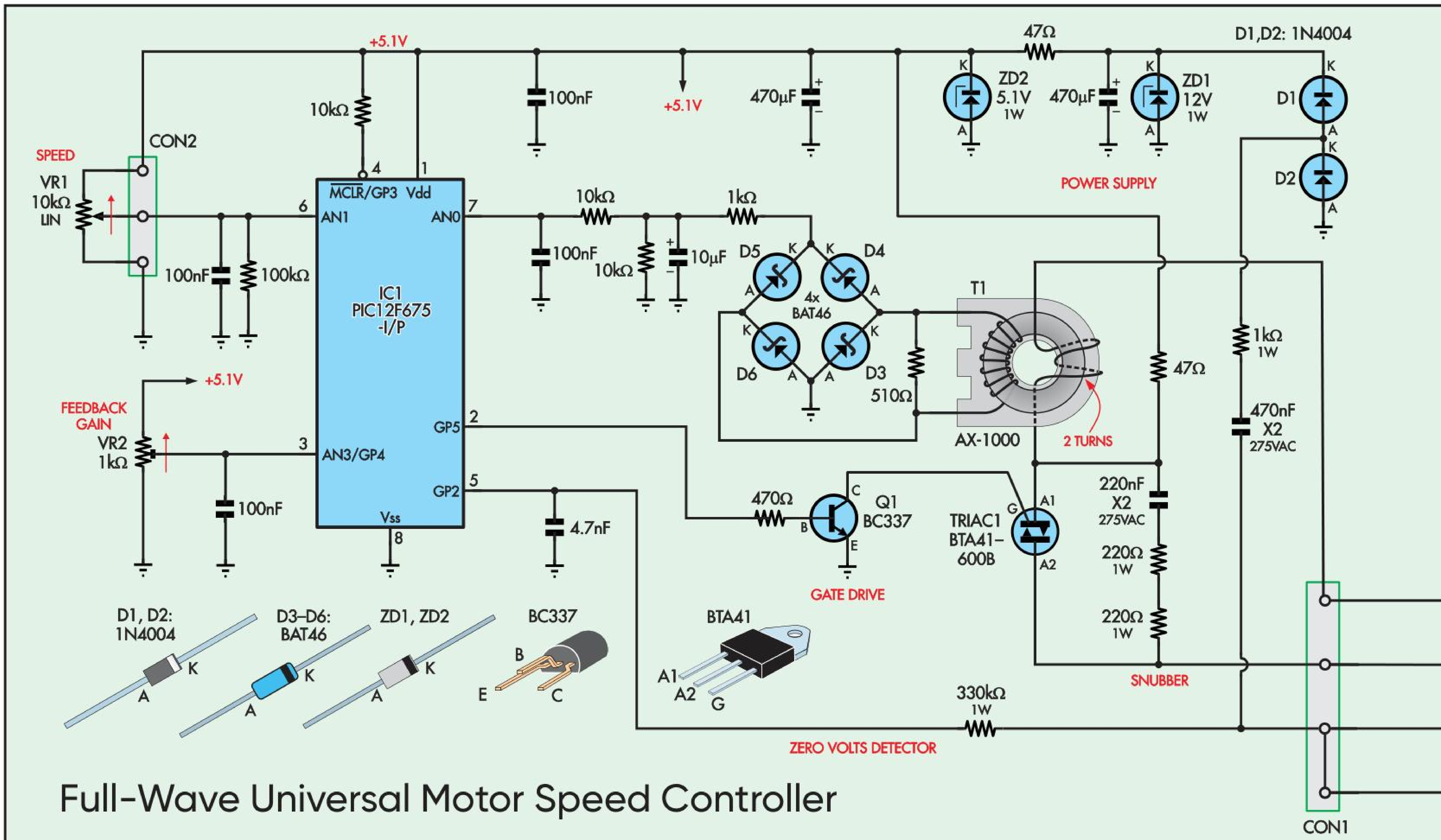
Trimpot VR2 is also connected across the 5.1V supply and has its wiper monitored by the AN3 input of IC1 at pin 3. This voltage sets the gain of the feedback to maintain motor speed load. It is also converted to a digital value within IC1.

The 100nF capacitors at the wiper of VR1 and VR2 are there to provide a low source impedance for the ADC sample and hold input.

Mains synchronisation

The timing of the triac's trigger pulses are critical to its correct operation; therefore, IC1 needs to monitor the mains voltage. This is done by the GP2 input of IC1, at pin 5. This monitors the mains neutral via a 330kΩ resistor and the signal is filtered with a 4.7nF capacitor.

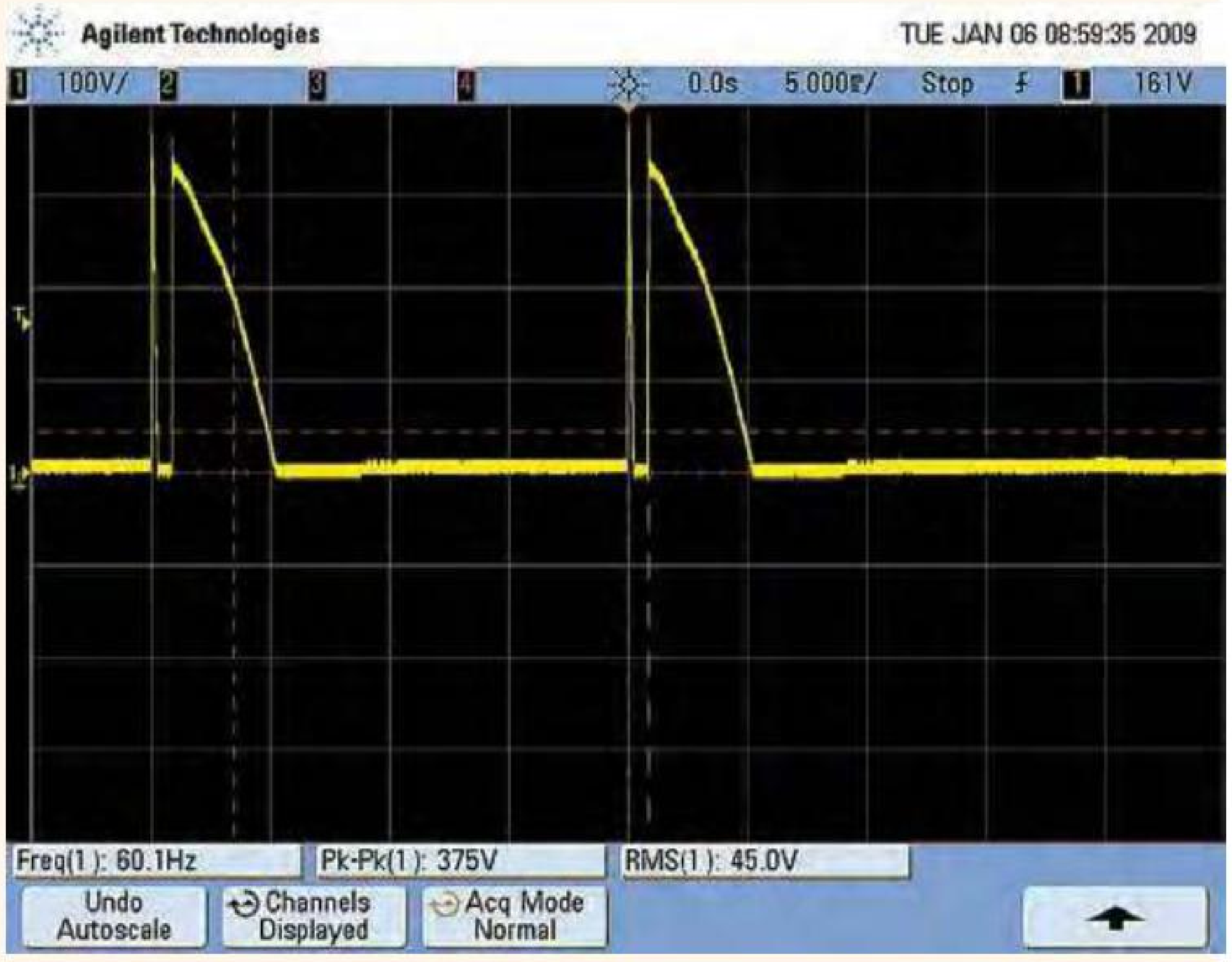
An interrupt in IC1 occurs whenever the voltage changes from a high (around 4V) to a low level (around 1V) and also from a low to a high.


+5.1V
10kΩ
100nF
+5.1V
470µF
47Ω
ZD2 5.1V 1W
470µF
ZD1 12V 1W
D1,D2: 1N4004
D1
D2
K
A
SPEED
VR1 10kΩ LIN
CON2
4
1
MCLR/GP3 Vdd
6
AN1
7
AN0
10kΩ
1kΩ
POWER SUPPLY
100nF
100kΩ
IC1 PIC12F675 -I/P
100nF
10kΩ
10µF
D5
D4
4x BAT46
D6
D3
510Ω
T1
AX-1000
2 TURNS
47Ω
1kΩ 1W
470nF X2 275VAC
+5.1V
FEEDBACK GAIN
VR2 1kΩ
3
AN3/GP4
GP5
2
GP2
5
Vss
8
100nF
4.7nF
470Ω
Q1 BC337
B C E
TRIAC1 BTA41–600B
G A1 A2
220nF X2 275VAC
220Ω 1W
220Ω 1W
GATE DRIVE
SNUBBER
D1, D2: 1N4004
D3–D6: BAT46
ZD1, ZD2
BC337
BTA41
A1 A2 G
330kΩ 1W
ZERO VOLTS DETECTOR
CON1

Full-Wave Universal Motor Speed Controller

Fig.1: The key components of the new controller circuit are the triac and the PIC12F675 microcontroller, IC1. IC1 monitors the speed potentiometer, VR1 at pin 6. It also monitors feedback gain potentiometer VR2, at pin 3, the current feedback via current transformer T1, at pin 7 and the mains waveform via a 330kΩ resistor at pin 5.

. . . in fact, there is no comparison in performance!



Scope3: now set for a lower speed from the electric drill, the triac is on for a shorter time and the RMS value of the waveform is considerably reduced to 45V. Note the frequency error caused by hash on the waveform.

That interrupt level occurs when the mains voltage swings through zero volts in either direction. The interrupt tells IC1 that the voltage of the mains has just passed through 0V.

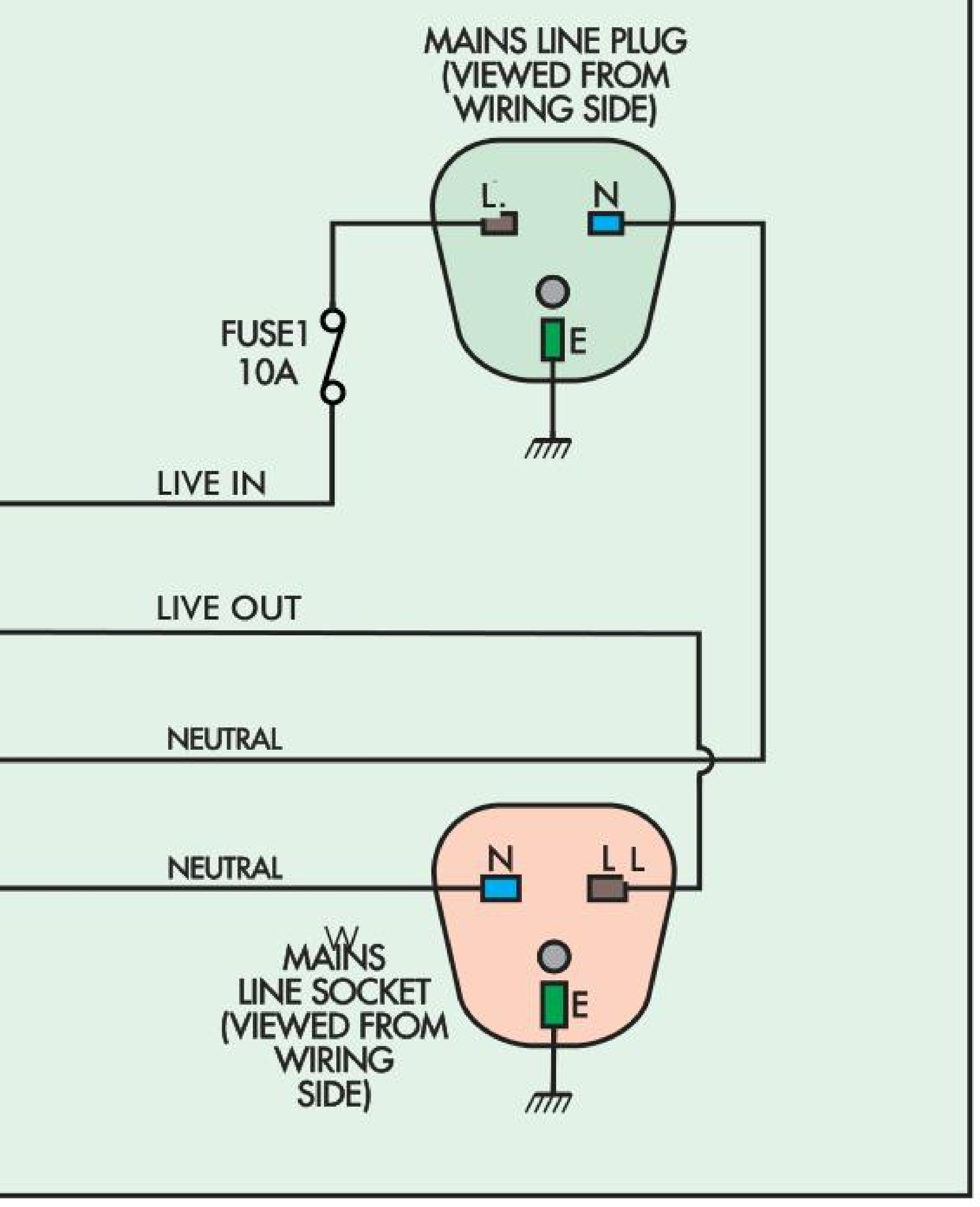
That allows IC1 to synchronise gate triggering with the mains waveform. Note that the 4.7nF capacitor at pin 5 introduces a phase lag (delay), but this is compensated for within IC1's software.

WARNING!

(1) This Speed Controller circuit operates directly from the 230VAC mains supply and contact with live components is potentially lethal.

(2) This circuit is not suitable for use with induction motors.

(3) Power tools with inbuilt fans must not be operated at low speeds for long periods, otherwise they may overheat.



MAINS LINE PLUG (VIEWED FROM WIRING SIDE)
L
N
E
FUSE1 10A
LIVE IN
LIVE OUT
NEUTRAL
NEUTRAL
N
L
E
MAINS LINE SOCKET (VIEWED FROM WIRING SIDE)

Current feedback

By now, you are probably wondering about the function of transformer T1 and the associated bridge rectifier. This is used to monitor the load current through the triac. T1 is a current transformer comprising a ferrite toroid with a 2-turn primary winding in series with the triac. The secondary winding has 1000 turns and it is loaded with a 510Ω resistor.

With this loading, the transformer produces a voltage of 800mV per amp of load current (the current through the motor being controlled).

This voltage is fed to the bridge rectifier consisting of four schottky diodes and the resulting DC is filtered with a 10µF capacitor.

The 1kΩ series resistor provides the attack time for the resulting current feedback signal while the 10kΩ resistor provides the decay, discharging the capacitor over time.

The current feedback signal is monitored at the AN0 input at pin 7 and the associated 10kΩ resistor and 100nF capacitor provide extra filtering, as well as limiting any current into the internal protection diodes at pin 7.

Transformer T1 provides the current feedback signal for IC1 which gives motor speed regulation, and trimpot VR2 is gain control for that function. You set VR2 to give the optimum speed regulation for the power tool under control.

Construction

With the exception of VR1 (the speed control potentiometer), the *Full-wave Universal Motor Speed Controller* is constructed entirely on a double-sided, plated-through PCB (printed circuit board) coded 10102181 and measuring 103 × 81mm. This is mounted inside a diecast box measuring 119 × 94 × 34mm.

Follow the overlay diagram shown in Fig.2. Assembly can begin by installing the resistors – check each resistor's value using a digital multimeter.

Following this, fit the diodes, which must be oriented as shown. Be careful: there are several different diode types – 1N4004 for D1 and D2, and BAT46 for D3 to D6; zener diodes are a 12V 1W type (1N4742) for ZD1 and a 5.1V 1W type (1N4733) for ZD2. If you get any of these mixed up, the circuit will not operate.

IC1 is mounted on an 8-pin DIL socket, so install this socket now, taking care to orient it correctly, with the notch facing towards the top of the PCB. (Leave IC1 out for the time being – we'll fit it later.) Q1 can be installed now.

Capacitors are placed next. The MKT capacitors and the polypropylene types are not polarised – follow their case codes for selelcting values. Electrolytic capacitors are almost always marked with their value (in µF) along with their polarity (usually the negative lead is marked with a stripe). They are polarised, so must be inserted with the polarity shown.

The screw terminals are next. The 3-way terminal block for CON2 is installed with the lead entries toward the lower edge of the PCB.

Now install the current transformer, T1. It does not matter which way it is oriented. The triac is fitted later.

Drilling the case

Further construction requires drilling holes in the diecast enclosure. A template is shown in Fig.4 for the end and side panel drilling details. The lid requires a 9.5mm diameter hole for potentiometer VR1 and a 4mm hole for the earth screw hole.

The PCB is mounted on the base of the case using M3 tapped spacers that are 6.3mm (or 8mm) long. Holes are required for these mounting holes on the base of the case.

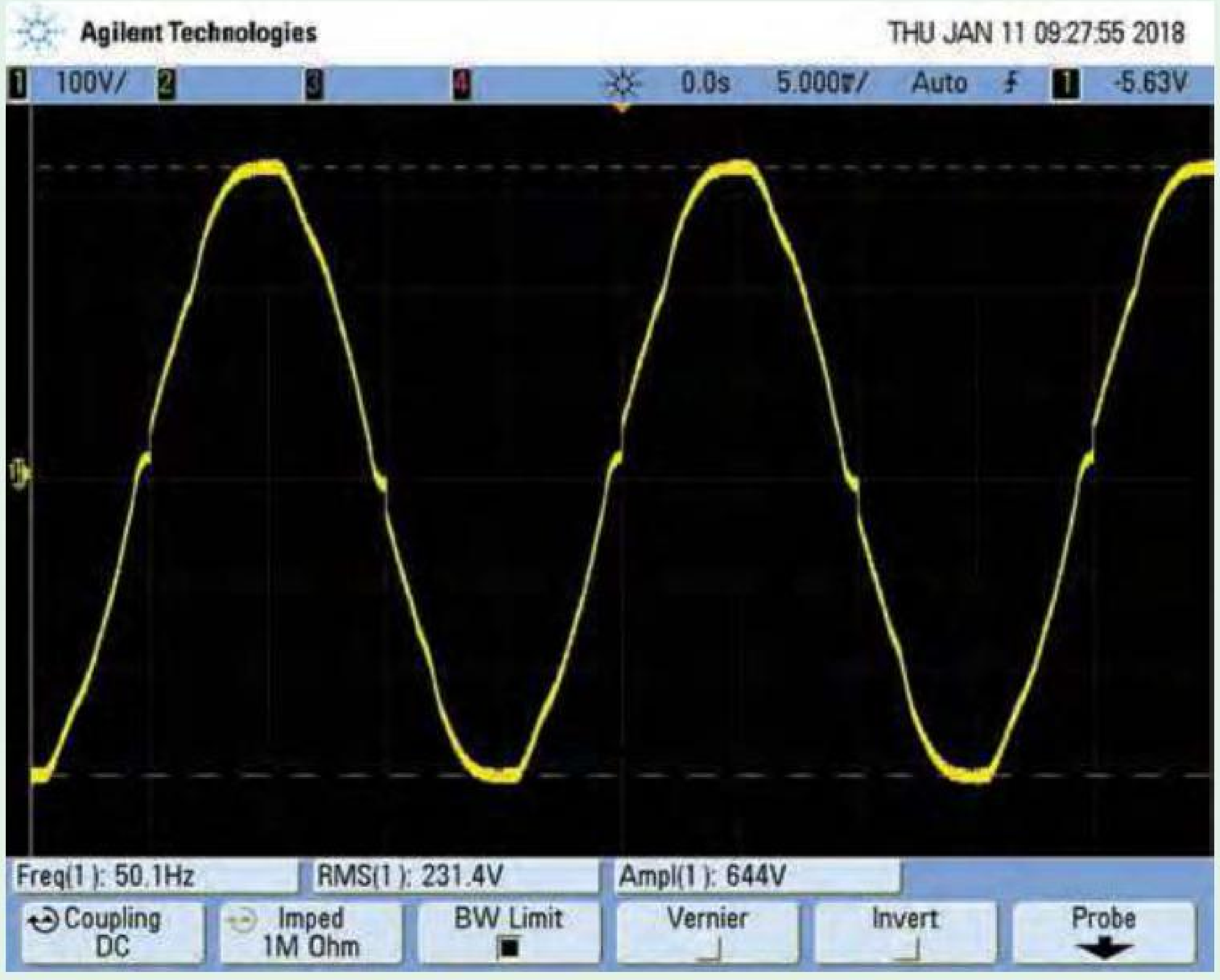
The CON1 screw terminal end of the PCB sits further away from the end of the box compared to the other end. This allows space for the cable gland nuts. Position the PCB in the case to use as a template and mark out the hole positions and drill out to 3mm.

Attach the 8 or 6.3mm-long spacers to the PCB. Then bend the triac leads up at 90° 4mm from the body of the triac. Insert the leads into the PCB from the underside. If you are using 6.3mm spacers, the underside pigtail leads from the components must be cut short to prevent close contact with the base of the case. They should be trimmed anyway, regardless of the spacer length.

The PCB can be secured to the case with screws from the underside into the tapped spacers. Mark out the triac mounting hole position on the base of the case.

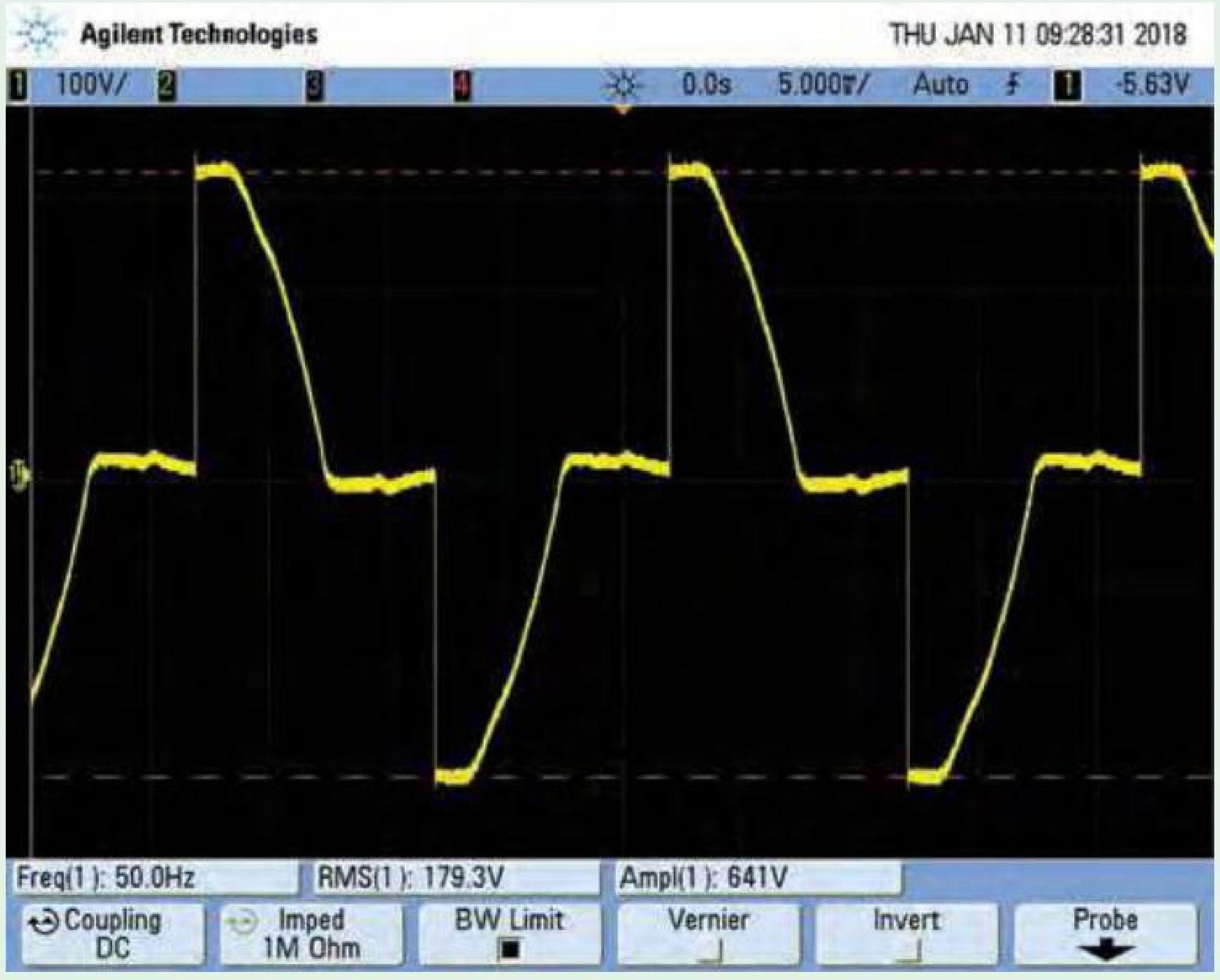
Drill speed controller performance waveforms

This series of scope grabs (and those overleaf) shows the triac Speed controller working with a 150W incandescent lamp load and a Bosch 500W 2-speed drill. In each case, the connection to the output of the speed controller is made via a 100:1 probe. The waveforms are identical to those taken with a fully isolated differential probe.



Freq(1): 50.1Hz
RMS(1): 231.4V
Ampl(1): 644V

Scope4: this shows the waveform at maximum output. There is only a very short period (<0.4ms) at the beginning of each half-cycle when the triac is off.



Freq(1): 50.0Hz
RMS(1): 179.3V
Ampl(1): 641V

Scope5: here the output is set to about half, corresponding to an RMS voltage of about 180V. (Scope 4, 5 and 6 are all with an incandescent lamp load.)

Remove the PCB again and drill out to 4mm. Clean away any metal swarf and slightly chamfer the hole edges. Reattach the PCB and adjust the triac lead height so the metal tab sits flush onto the flat surface.

Secure the triac with the M3 screw and nut. The metal tab is internally isolated from the leads and so does not require any further insulation between its tab and case. Solder the triac leads on the top of the PCB and trim the leads close to the PCB.

Now remove the screws to gain access to the underside of the PCB and solder the triac leads from the underside of the PCB. The four rubber feet can be attached to the base of the case now.

Two holes are required in the lid – one for the speed control pot (9.5mm) and the other for the earth screw (4mm).

If you use a countersunk-head earth screw and countersink the earth screw hole appropriately, it can be mounted **under** the panel label (looks neater). Otherwise, cut holes in the panel label (with a sharp knife) when the label is stuck on.

The panel label file can be downloaded from the *PE* website. To produce a front panel label, you have several options. For a more robust label, print as a mirror image onto clear overhead projector film (using film suitable for your type of printer). Attach the label printed side down to the lid with a light coloured or clear silicone sealant.

Alternatively, you can print onto a synthetic sticky label that is suitable for inkjet printers or laser printers. Then affix the label using the sticky back adhesive.

Wiring

Cut the 10A extension lead into two to provide one lead with a plug on the end and another with a socket. Where the lead is cut depends on how long you prefer each lead.

You may prefer a long plug cord and short socket lead so the motor appliance is located near to the controller, or the lead can be cut into two equal lengths.

Before cutting make sure you have sufficient length to strip back the insulation, as detailed in the next two paragraphs.

What motors can be controlled?

We've noted elsewhere in this article that this controller suits the vast majority of power tools and appliances. These generally use universal motors and are series-wound motors with brushes. Incidentally, they're called universal motors because they can operate on both AC and DC.

You **cannot** use this Speed Controller with any appliance which has an electronic speed control built in, whether part of the trigger mechanism or with a separate speed dial.

This restriction does not apply to tools such as electric drills which provide a choice of two speeds via inbuilt reduction gears.

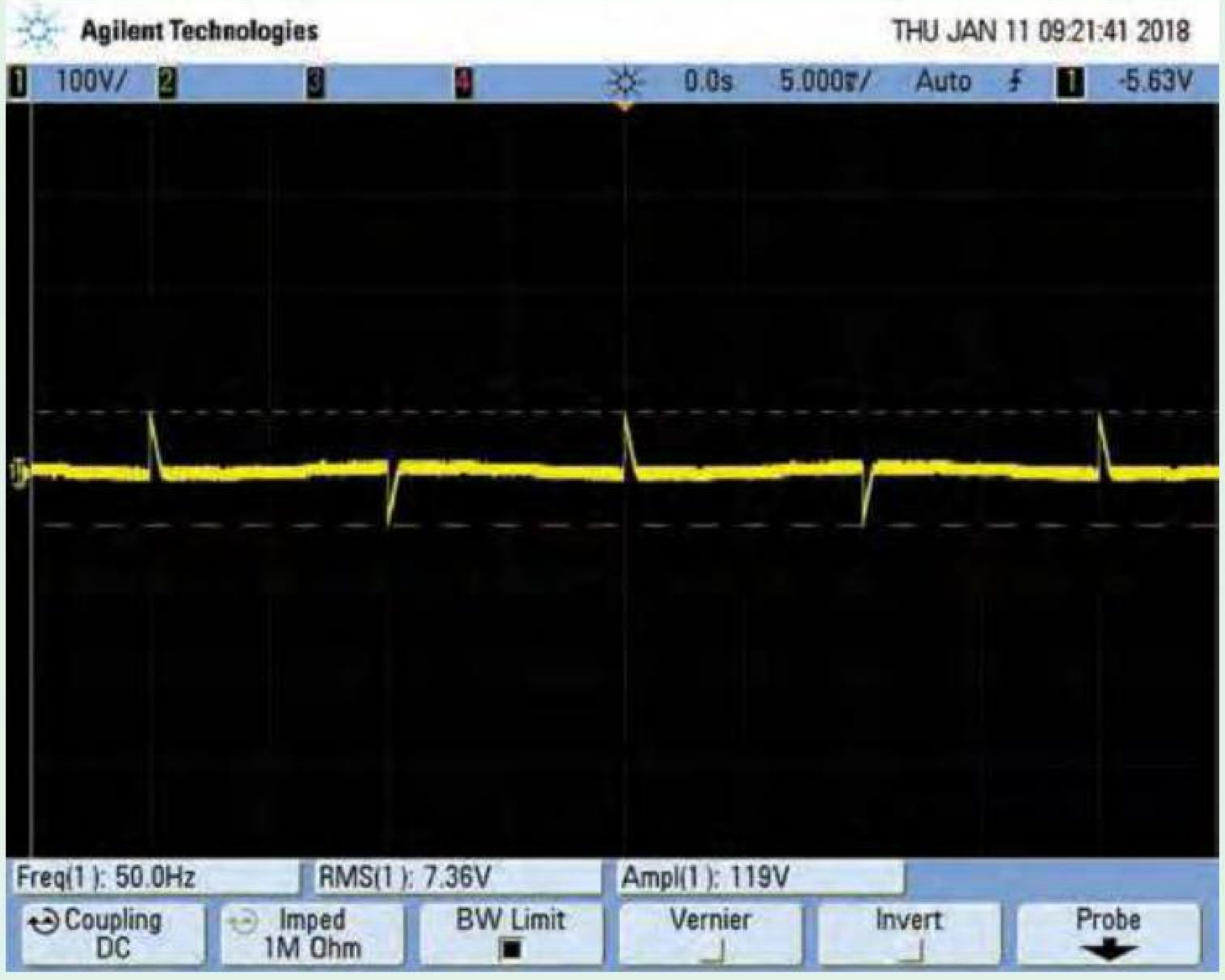
What about induction motors?

We have strongly warned against using any of our previous AC speed controls with induction motors, for two reasons. First, the output of our previous designs is variable unfiltered DC – and that will not run an induction motor, which requires a variable supply frequency for its speed to be varied. Second, connecting an induction motor to any of our previous speed controls usually resulted in serious circuit damage as well possibly burning out the induction motor itself.

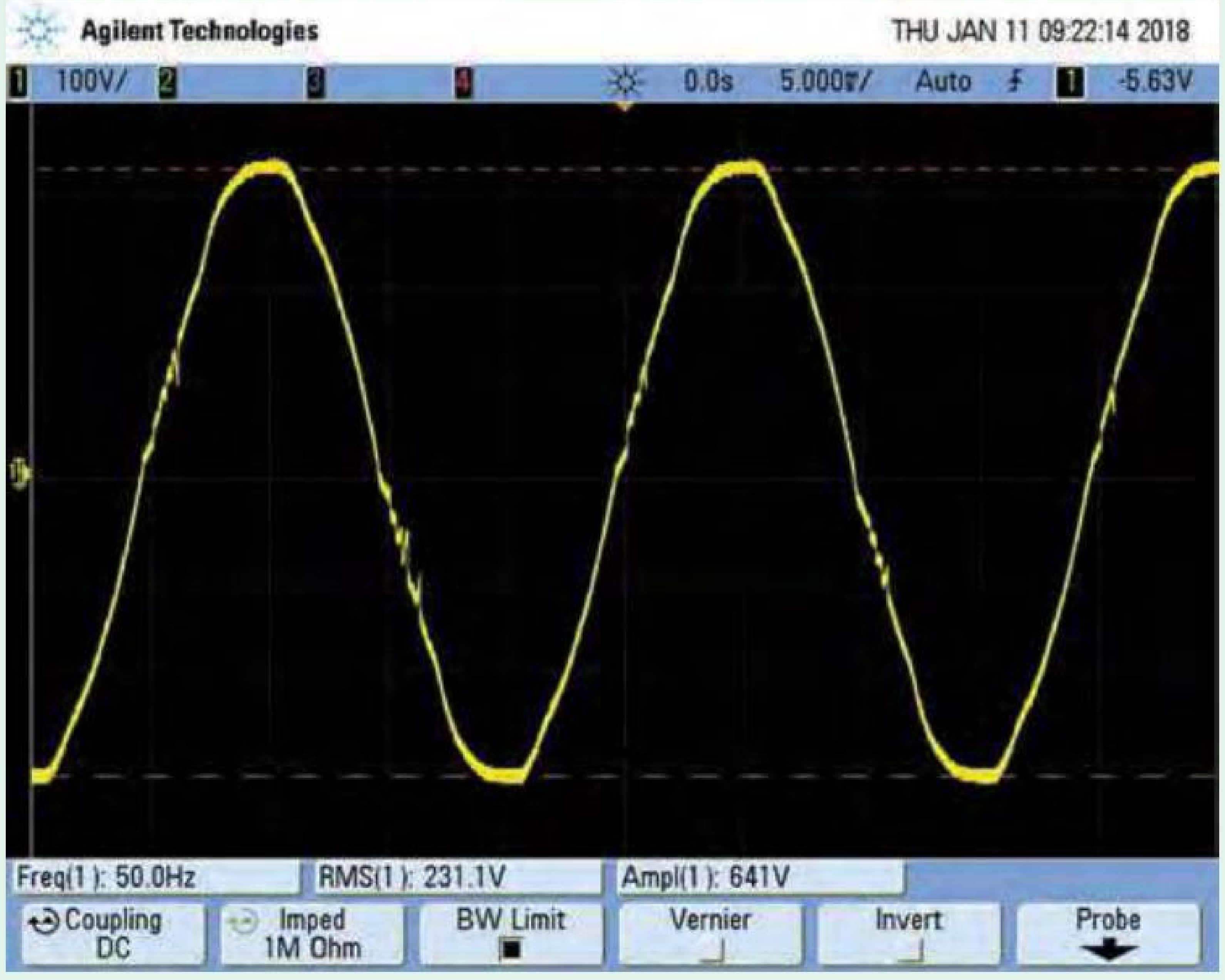
That won't happen with this new Speed Controller **but it's use here is pointless – it does not vary the mains frequency so it cannot vary the motor speed**. You are unlikely to do any damage to the Speed Controller though.

So how do you actully identify an induction motor? Most induction motors used in domestic appliances will be 2-pole or 4-pole and always operate at a fixed speed, which is typically 2850 rpm for a 2-pole or 1440 rpm for a 4-pole unit. The speed will be on the nameplate. Bench grinders typically use 2-pole induction motors.

If you do need to control this type of motor, use the 1.5kW Induction Motor Controller published in January and February 2019.


Agilent Technologies
THU JAN 11 09:21:41 2018
1 100V/ 2 3 4 0.0s 5.000ms/ Auto 1 -5.63V
Freq(1): 50.0Hz
RMS(1): 7.36V
Ampl(1): 119V
Coupling DC
Imped 1M Ohm
BW Limit
Vernier
Invert
Probe

Scope6: the output is set to the minimum whereby the triac is still firing. The RMS voltage is 7.36V and the lamp filament is not even glowing.


Agilent Technologies
THU JAN 11 09:22:14 2018
1 100V/ 2 3 4 0.0s 5.000ms/ Auto 1 -5.63V
Freq(1): 50.0Hz
RMS(1): 231.1V
Ampl(1): 641V
Coupling DC
Imped 1M Ohm
BW Limit
Vernier
Invert
Probe

Scope7: here the output is set to maximum but the load is the 500W drill. The hash on the waveform is due to the motor's commutator.

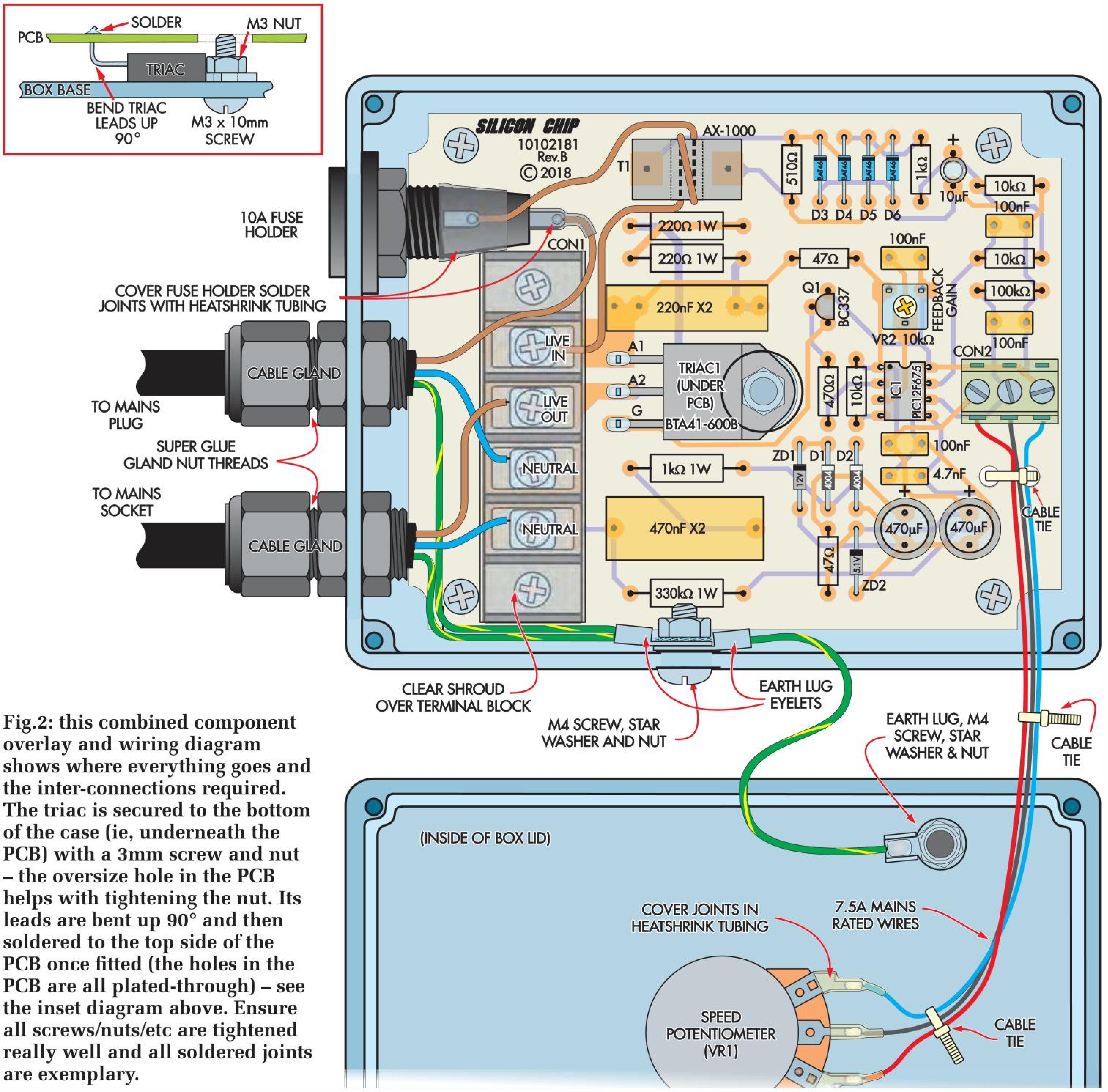
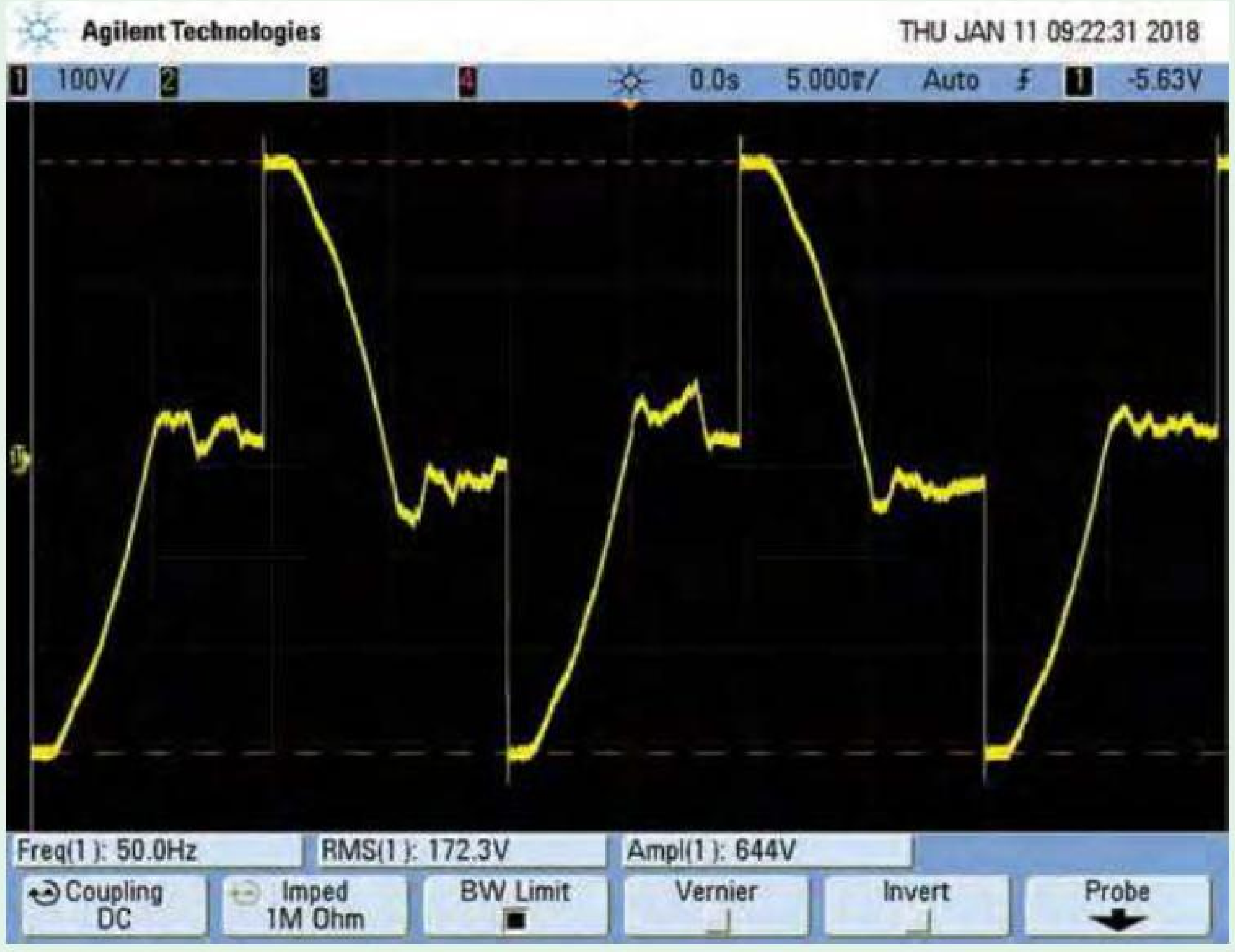
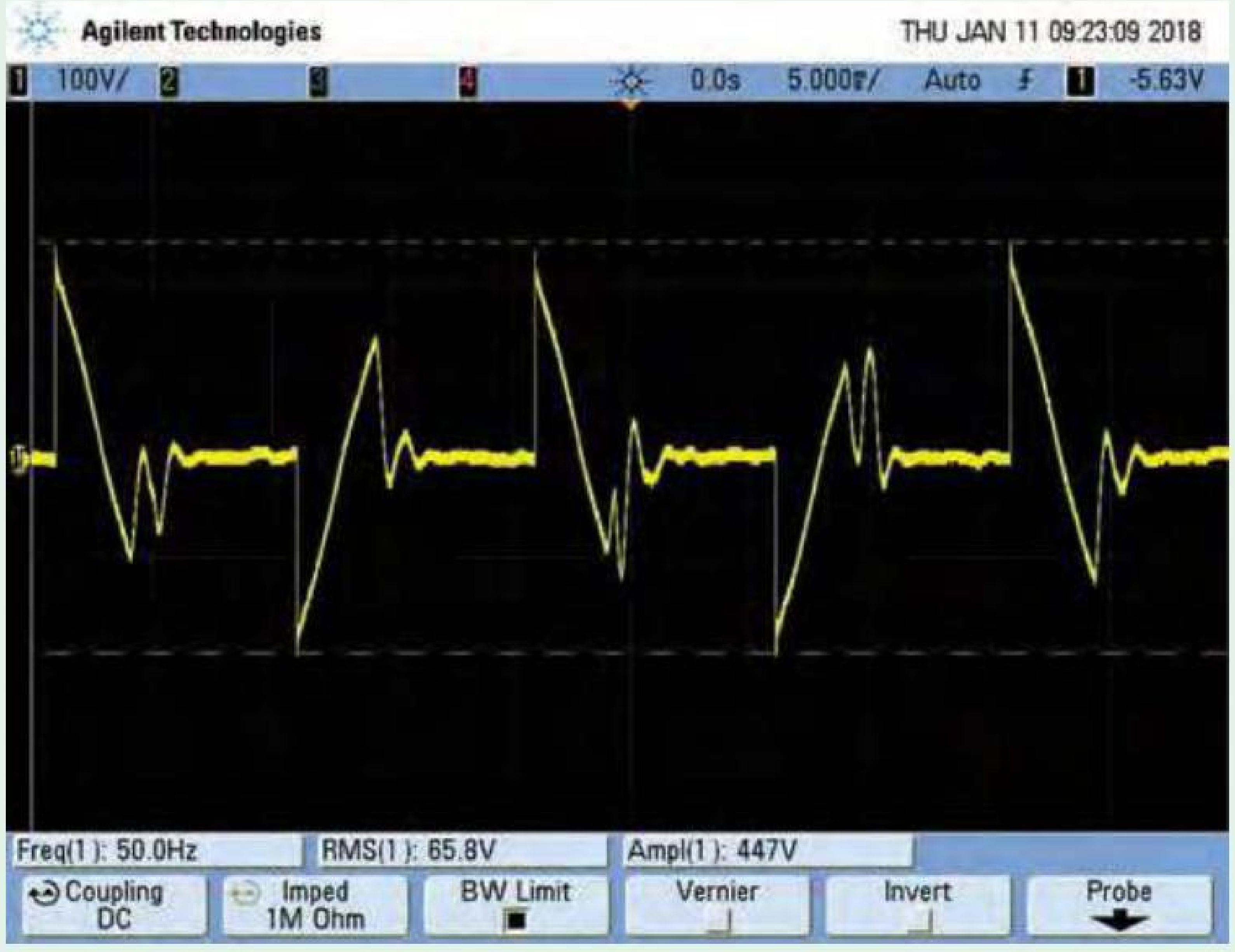

PCB
SOLDER
M3 NUT
TRIAC
BOX BASE
BEND TRIAC LEADS UP 90°
M3 x 10mm SCREW
SILICON CHIP
10102181 Rev.B © 2018
T1
AX-1000
10A FUSE HOLDER
CON1
COVER FUSE HOLDER SOLDER JOINTS WITH HEATSHRINK TUBING
CABLE GLAND
TO MAINS PLUG
SUPER GLUE GLAND NUT THREADS
TO MAINS SOCKET
CABLE GLAND
LIVE IN
LIVE OUT
NEUTRAL
NEUTRAL
220Ω 1W
220Ω 1W
220nF X2
A1
A2
G
TRIAC1 (UNDER PCB)
BTA41-600B
1kΩ 1W
470nF X2
330kΩ 1W
510Ω
D3 D4 D5 D6
BAT46
1kΩ
10µF
10kΩ
100nF
47Ω
100nF
10kΩ
100kΩ
100nF
Q1
BC337
VR2 10kΩ
FEEDBACK GAIN
CON2
470Ω
10kΩ
IC1
PIC12F675
100nF
4.7nF
ZD1 D1 D2
12V
4004
4004
47Ω
5.1V
ZD2
470µF
470µF
CABLE TIE
CLEAR SHROUD OVER TERMINAL BLOCK
M4 SCREW, STAR WASHER AND NUT
EARTH LUG EYELETS
EARTH LUG, M4 SCREW, STAR WASHER & NUT
CABLE TIE
(INSIDE OF BOX LID)
COVER JOINTS IN HEATSHRINK TUBING
7.5A MAINS RATED WIRES
SPEED POTENTIOMETER (VR1)
CABLE TIE

Fig.2: this combined component overlay and wiring diagram shows where everything goes and the inter-connections required. The triac is secured to the bottom of the case (ie, underneath the PCB) with a 3mm screw and nut – the oversize hole in the PCB helps with tightening the nut. Its leads are bent up 90° and then soldered to the top side of the PCB once fitted (the holes in the PCB are all plated-through) – see the inset diagram above. Ensure all screws/nuts/etc are tightened really well and all soldered joints are exemplary.


Agilent Technologies
THU JAN 11 09:22:31 2018
100V/
0.0s
5.000ms/
Auto
-5.63V
Freq(1): 50.0Hz
RMS(1): 172.3V
Ampl(1): 644V
Coupling DC
Imped 1M Ohm
BW Limit
Vernier
Invert
Probe

Scope8: the output is set to about half with the 500W drill as a load. The RMS voltage is just less than 180V, the maximum you could expect with a conventional half-wave SCR speed control.

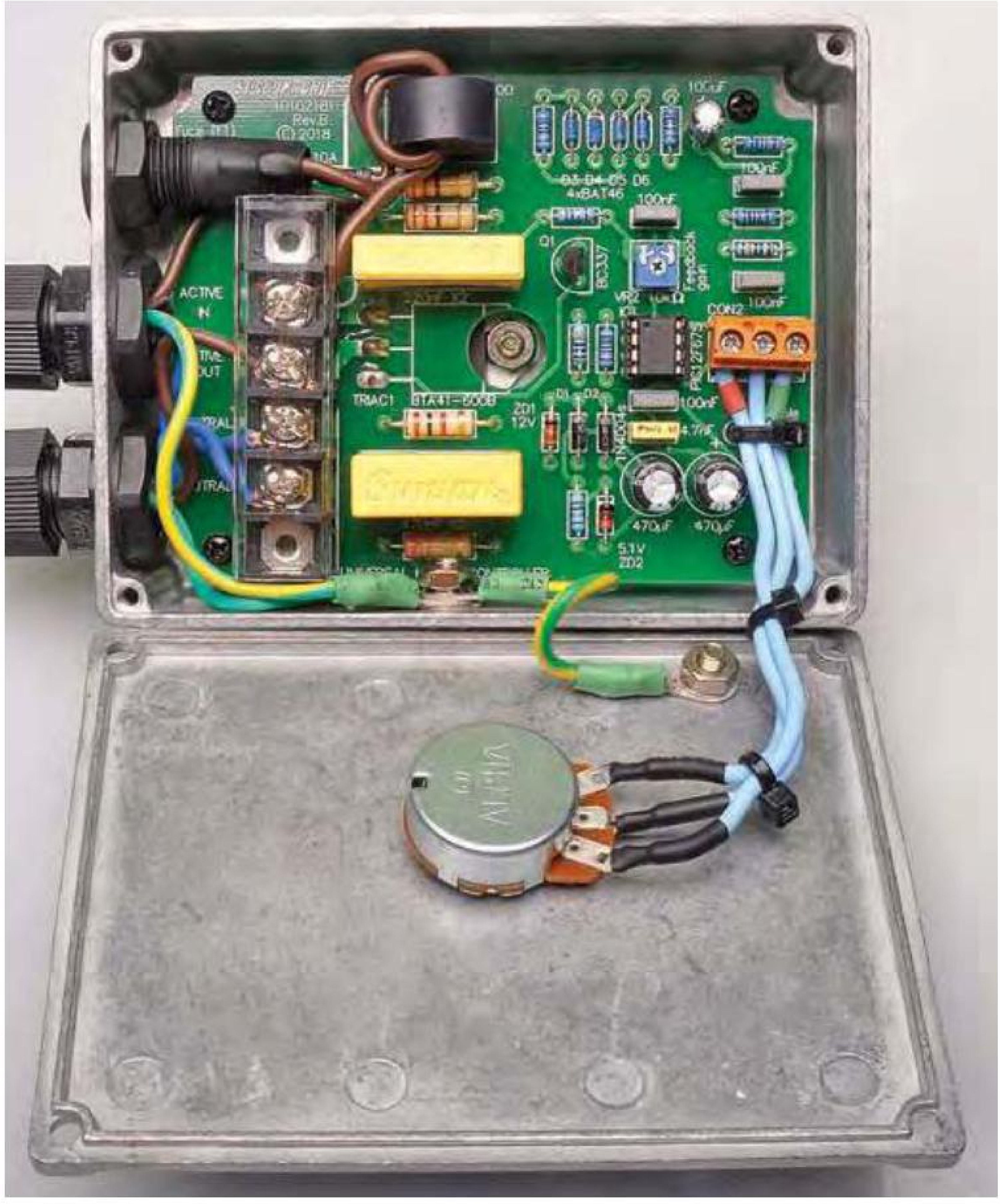

Agilent Technologies
THU JAN 11 09:23:09 2018
100V/
0.0s
5.000ms/
Auto
-5.63V
Freq(1): 50.0Hz
RMS(1): 65.8V
Ampl(1): 447V
Coupling DC
Imped 1M Ohm
BW Limit
Vernier
Invert
Probe

Scope9: here the output is set to the minimum that will give useful smooth low speed running from the drill. Again, the severe hash on the waveform is due to the motor's commutator.

Make sure the plug lead and socket lead are placed in the correct gland and wired as shown.

First, the socket (output) lead: you need a 100mm length of earth wire (green/yellow stripe) for the connection between the chassis and lid, so strip back the outside sheath insulation by about 200mm. Then cut the blue neutral wire and brown live wires to 50mm and connect them to their respective terminals on the terminal block.

You should be left with 100mm of earth wire (green/yellow stripe) which is routed around the edge of the PCB and twists with the earth wire from the plug (input) lead to be crimped into one of the earth lugs. The spare 150mm brown wire can be used later to connect from the fuse to the CON1 terminal via the transformer, T1. This has two turns of the live wire looped through the transformer hole.


ACTIVE IN
TRIAC1
BTA41-600B
CON2
470µF
100nF
ZD1 12V
5.1V ZD2
4xBAT46
ALPHA

The lid, with front panel affixed, 'opens out' from the box as shown in this photo. Make sure the wires to the speed pot are all 250VAC mains-rated (don't use low-voltage rainbow cable!) and use cable ties and heatshrink where shown above and in Fig.2.

The plug lead outside sheath insulation should be stripped back to expose 100mm of wire. This leaves sufficient lead length. All three wires are passed through the cable glands and connect as shown in Fig.2. Cut the neutral wire to 50mm and strip back the insulation before connecting the neutral (blue) wire to the terminal block

The live (brown) wire solders direct to the fuseholder. 10mm-diameter heatshrink tubing should first be placed over live (brown) wire which slides up and over the fuseholder after soldering to cover the side fuseholder terminal.

Similarly, 3mm-diameter heatshrink tubing is used to cover the fuseholder end terminal. Once both connections are soldered, pass the heatshrink over the join and shrink.

Now twist the ends of the input earth (green/yellow stripe) wire and the output earth wire together and crimp into one of the eyelet earth lugs.

Cut VR1's shaft to 12mm long and file the edges smooth. Then attach the three 100mm lengths of 7.5A mains-rated wire to the three VR1 terminals and cover with the 3mm heatshrink tubing. The other ends connect to CON2.

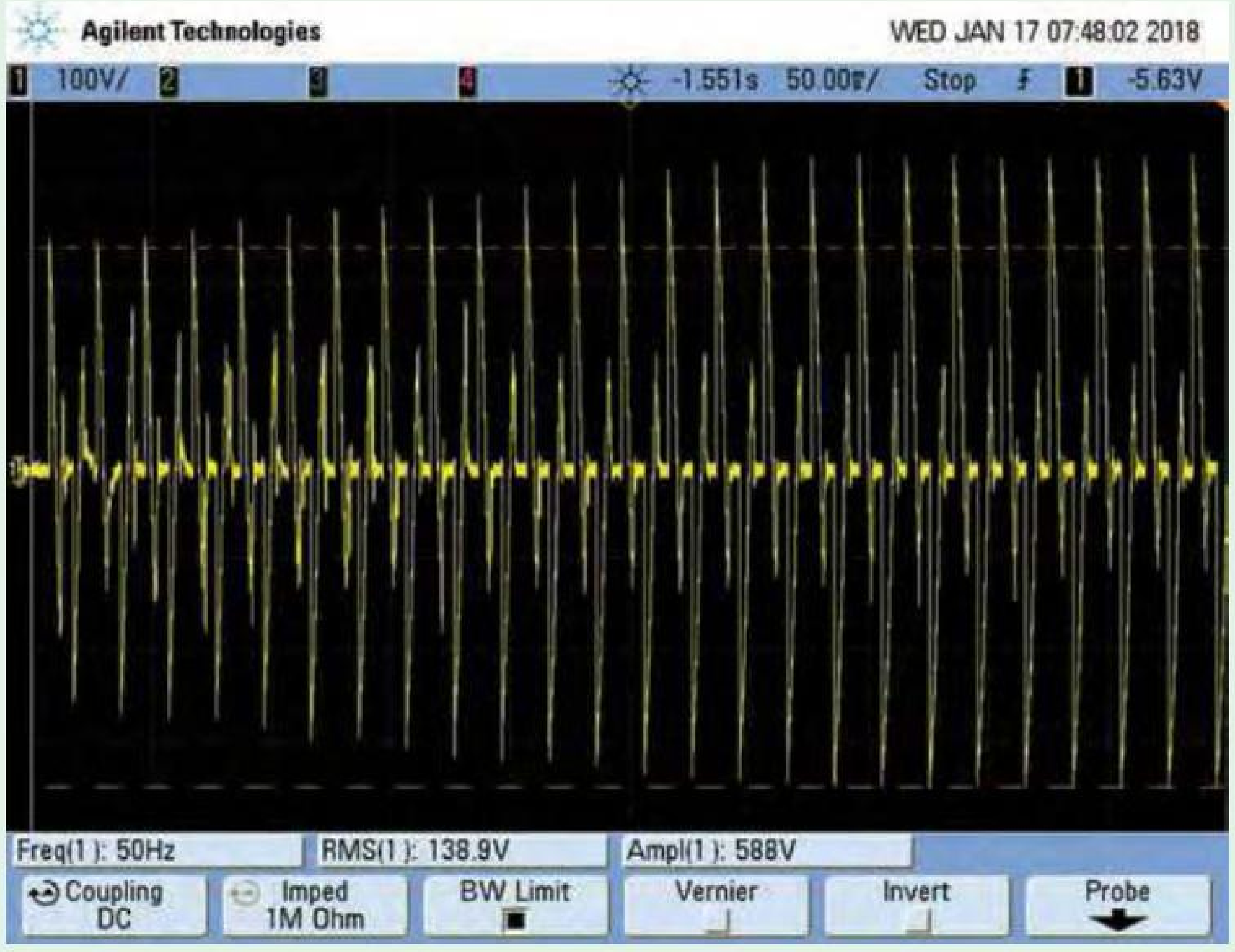
These wires are secured using a cable tie that feeds through holes in the PCB. Attach VR1 to the lid of the case – note that the potentiometer must be located as shown (ie, leads emerging from the right) so it fits between the two mains rated capacitors on the PCB.

Fit the knob – you may need to lift out the knob cap with a hobby knife and re-orient the cap so its pointer position matches the rotation marks on the panel.

That 100mm length of earth wire you cut off from the output lead can now be crimped into two eyelet lugs, which are screwed to the underside of the box lid and the earth screw on the side of the case using M4 screws, star washers and nuts. Ensure that the nuts are fully tightened.

Final assembly

Apply a smear of heatsink compound to the underside of the triac before installing the PCB inside the case. Again, the tab of the triac is insulated, so it can contact the case with safety.


Agilent Technologies
WED JAN 17 07:48:02 2018
1 100V/ 2 3 4
-1.551s 50.00ms/ Stop 1 -5.63V
Freq(1): 50Hz
RMS(1): 138.9V
Ampl(1): 588V
Coupling DC
Imped 1M Ohm
BW Limit
Vernier
Invert
Probe

Scope10: the ramp-up of the triac triggering angle during soft startup. The full ramp-up takes more than one second.

The last components to be inserted are IC1 (taking care it is oriented correctly), the 10A fuse into its holder and the cover for the barrier terminals (CON1) – it is simply pressed on to cover the screw terminals. Finally, rotate VR2 fully anticlockwise to initially disable feedback.

Check your construction carefully and especially check that the earth wires (green/yellow striped) actually connect together the case, the lid and the earth pins on both the mains plug and socket. Check this with a multimeter set to read low ohms.

The cable glands need to be tightened to hold the mains cords in place. Because these are easily undone, the thread of the glands should have a drop of super glue applied to the threads before tightening. This way the glands cannot be undone. Attach the lid to the case using the four screws supplied with the case – **don't be tempted to run the speed controller without the lid in place!**

Testing

Connect up a universal motor appliance (eg, an electric drill) to the controller, apply power and check the motor can be controlled when adjusting the speed potentiometer.

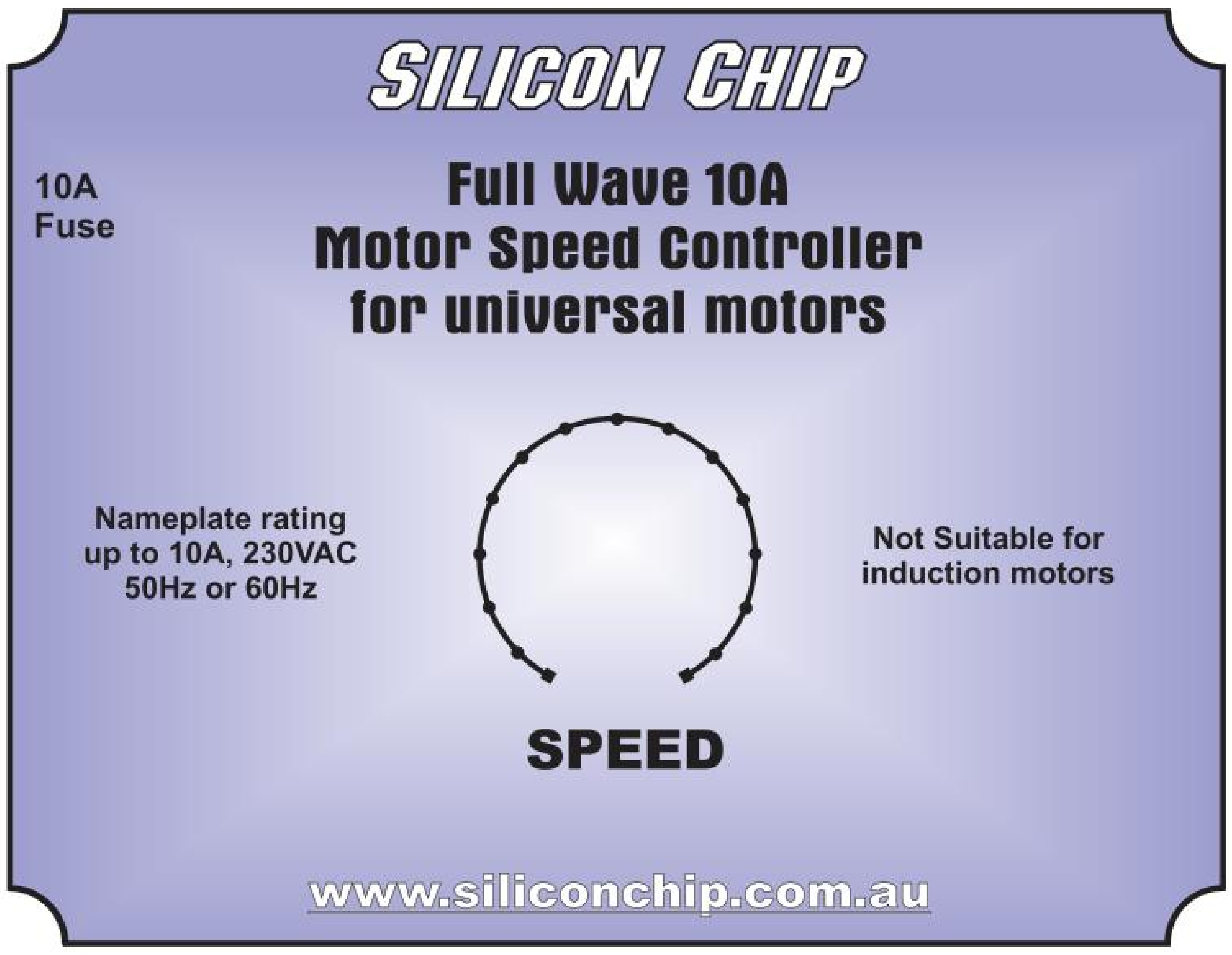

SILICON CHIP
10A Fuse
Full Wave 10A Motor Speed Controller for universal motors
Nameplate rating up to 10A, 230VAC 50Hz or 60Hz
Not Suitable for induction motors
SPEED
www.siliconchip.com.au

Fig.3: front panel artwork (shown here approximately 3/4 full size) which is designed to be affixed to the case lid. This artwork can be downloaded from the *PE* website.

Parts list – Full Wave Universal Motor Speed Controller

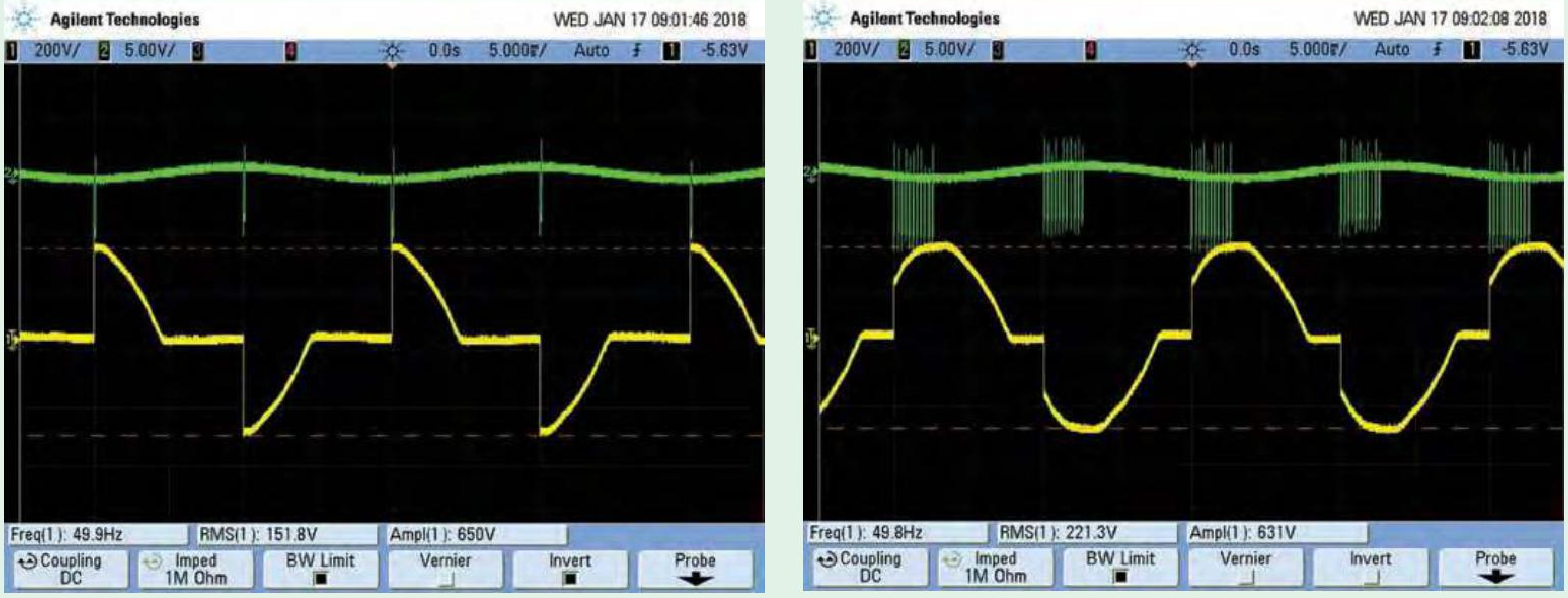
1 PCB coded 10102181, measuring 103 × 81mm
1 diecast box 119 × 94 × 34mm [Jaycar HB-5067]
1 Talema AX-1000 10A current transformer (T1) [RS Components 775-4928]
1 M205 10A safety panel mount fuse holder (F1) [Altronics S5992]
1 M205 10A fuse
1 4-way PCB mount terminal barrier (CON1) [Jaycar HM-3162]
1 3-way PCB mount screw terminals with 5.08mm spacings (CON2)
2 cable glands for 5-10mm cable
1 DIL-8 IC socket
1 2m 250V 10A mains extension lead (cut in half to form mains input and output leads)
4 4mm eyelet lugs
4 8mm or 6.3mm M3 tapped nylon standoffs
1 M3 × 10mm screw (for triac mounting)
1 M3 nut and washer
2 M4 × 10mm screws (CSK head preferred)
2 4mm ID star washers
2 M4 nuts
8 M3 × 5mm screws
4 stick-on rubber feet
1 20mm length of 12mm-diameter heatshrink tubing
1 80mm length of 3mm-diameter heatshrink tubing
1 25mm length of 6mm-diameter green heatshrink tubing if required for chassis lugs
3 150mm lengths of 7.5A mains-rated wire for VR1
3 100mm-long cable ties

Semiconductors
1 PIC12F675 programmed with 1010218A.hex (IC1)
1 BTA41-600B insulated tab 40A 600V triac (triac1) [element14 1057288 or RS 687-1007]
1 BC337 NPN transistor (Q1)
1 12V 1W (1N4742) zener diode (ZD1)
1 5.1V 1W (1N4733) zener diode (ZD2)
2 1N4004 1A diodes (D1,D2)
4 BAT46 schottky diodes (D3-D6)

Capacitors
2 470µF 16V PC electrolytic
1 10µF 16V PC electrolytic
1 470nF 275VAC X2 class
1 220nF 275VAC X2 class
4 100nF 63V or 100V MKT polyester
1 4.7nF 63V or 100V MKT polyester

Resistors (0.25W, 1% unless specified)
1 330kΩ 1W carbon film
1 100kΩ
3 10kΩ
1 1kΩ
1 1kΩ 1W carbon film
1 510Ω
1 470Ω
2 220Ω 1W carbon film
2 47Ω
1 linear 10kΩ 24mm potentiometer (VR1)
1 10kΩ mini, top adjust trimpot (3386F style) (VR2)

Miscellaneous
1 knob to suit VR1
Super glue, heatsink compound, solder


Agilent Technologies
WED JAN 17 09:01:46 2018
1 200V/ 2 5.00V/ 3 4
0.0s 5.000ms/ Auto 1 -5.63V
Freq(1): 49.9Hz
RMS(1): 151.8V
Ampl(1): 650V
Coupling DC
Imped 1M Ohm
BW Limit
Vernier
Invert
Probe
Agilent Technologies
WED JAN 17 09:02:08 2018
1 200V/ 2 5.00V/ 3 4
0.0s 5.000ms/ Auto 1 -5.63V
Freq(1): 49.8Hz
RMS(1): 221.3V
Ampl(1): 631V
Coupling DC
Imped 1M Ohm
BW Limit
Vernier
Invert
Probe

Scope11 and 12: these show how the triac triggering varies, depending on the speed setting. At low speed settings, there is only one trigger pulse during each mains half-cycle. At higher power levels, there are multiple trigger pulses during each half-cycle to ensure that the triac stays turned on, in spite of the lagging load current (due to the inductive motor load).

Once you have verified that it works, **switch off power and unplug the mains plug** from the mains outlet. Then remove the lid and adjust VR2 half way. Re-attach the lid and apply power again and check the speed regulation of the motor under load.

Trimpot VR2 may need some further adjustment; anticlockwise if the motor speeds up under load and clockwise if the speed drops off too markedly under load.

Note that any adjustment of VR2 must **only** be done with the power off and mains plug disconnected. This means that adjustment is a trial and error process. **Power should only re-applied after the lid is re-attached.**

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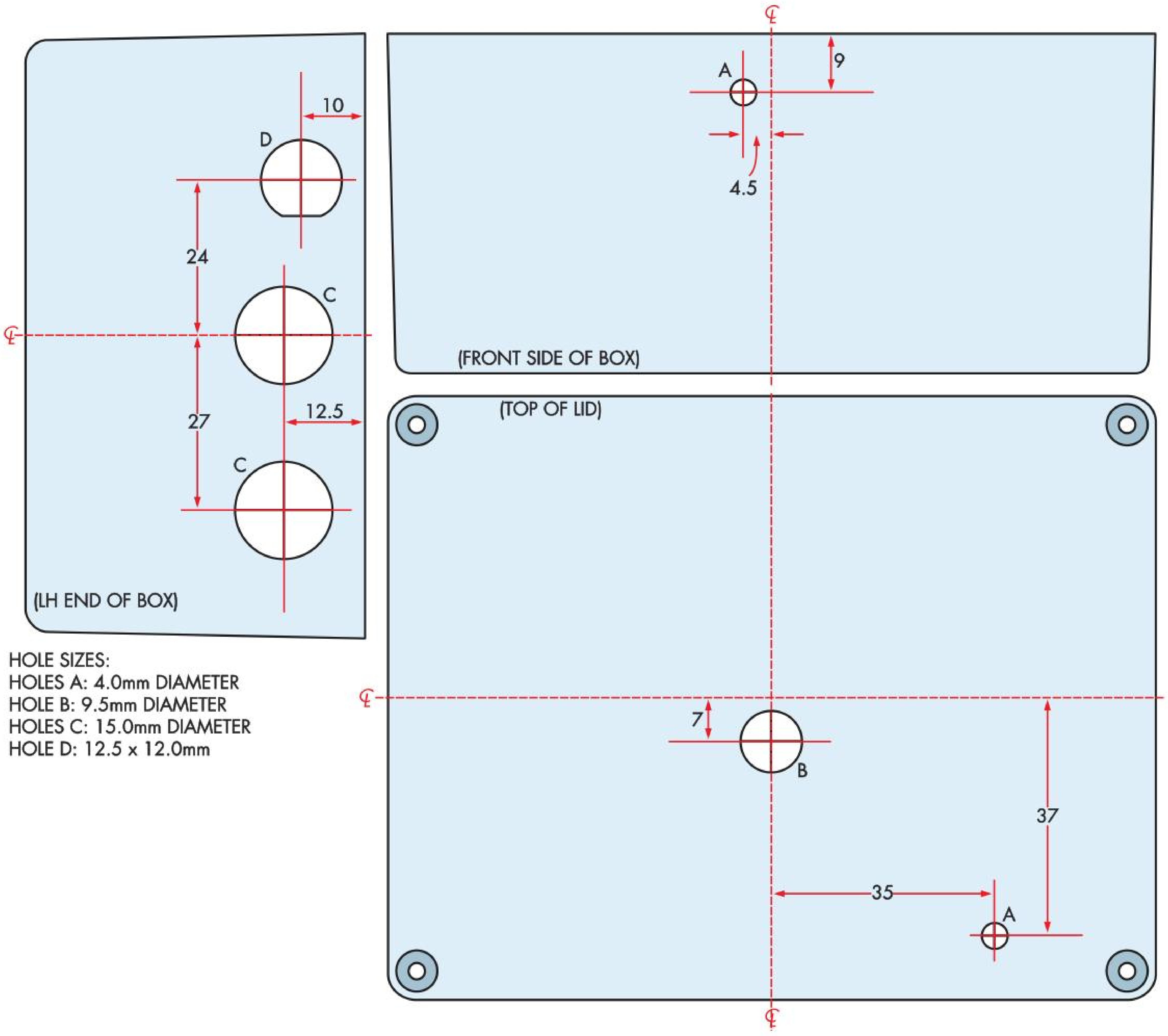
10
D
24
C
27
12.5
C
(LH END OF BOX)
HOLE SIZES:
HOLES A: 4.0mm DIAMETER
HOLE B: 9.5mm DIAMETER
HOLES C: 15.0mm DIAMETER
HOLE D: 12.5 x 12.0mm
A
9
4.5
(FRONT SIDE OF BOX)
(TOP OF LID)
7
B
37
35
A

Fig.4: (above) drilling detail of the specified diecast box, reproduced approximately 3/4 full size. Note that the hole for the fuseholder is not circular – the D-shape keeps the fuseholder from turning when a fuse is being inserted or removed. The 3mm diameter hole for the triac in the bottom of the box is not shown –use the PCB to locate it. This artwork can be downloaded from the *PE* website.

(Left) Three holes are required in the end of the case – the two on the right are 15mm to suit the cable glands, while the hole on the left is nominally 12.5mm but is 'D' shaped to hold the fuseholder in place. On the lid, a 9.5mm hole to house the speed control pot sits slightly off-centre with a 4mm hole (on the left in this photo) for the lid earthing screw. As mentioned in the text, if this hole is shaped to accept a countersunk-head screw, it can go underneath the label and so not be visible.

Win a Microchip SAM L21 Xplained Pro Evaluation Kit

Practical Electronics is offering its readers the chance to win a Microchip SAM L21 Xplained Pro Evaluation Kit (ATSAML21-XPRO-B).

The SAM L21 Xplained Pro evaluation kit is for evaluating and prototyping with the ultra-low-power SAM L21 ARM Cortex-M0+ based microcontrollers.

The Microchip SAM L family of microcontrollers are built with innovative picoPower Technology to deliver best-in-class low-power consumption down to 25µA/MHz in active mode, under 100nA in sleep mode and fast wake-up times of 1.2µs.

These MCUs have achieved an EEMBC-certified ULPMark Score of 410, which is the highest score for an ARM Cortex-M23 or ARM Cortex-M0+ class device. In addition to ultra-low-power capabilities, these devices feature an enhanced peripheral touch controller, chip-level robust security, ARMTrustZone Technology, AES, full-speed USB host and device, event system and sleepwalking, 12-bit analogue, built in op amps and much more.

A rich set of peripherals, flexibility and ease of use combined with ultra-low-power consumption make the SAM L21 ARM Cortex-M0+ based microcontroller series ideal for IoT, wireless and any system that needs large memories and ultra-low power consumption.

The SAM L21 is designed for simple and intuitive migration between SAM L devices with identical peripheral modules, compatible code and a linear address map, and is compatible with the SAM D family of general-purpose MCUs.

Worth $66.00 (approx £50.00) each

Microchip
SAM L21 Xplained Pro
Evaluation Kit

Free-to-enter competition

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Closing date

The closing date for this offer is 31 July 2019.

March 2019 winners

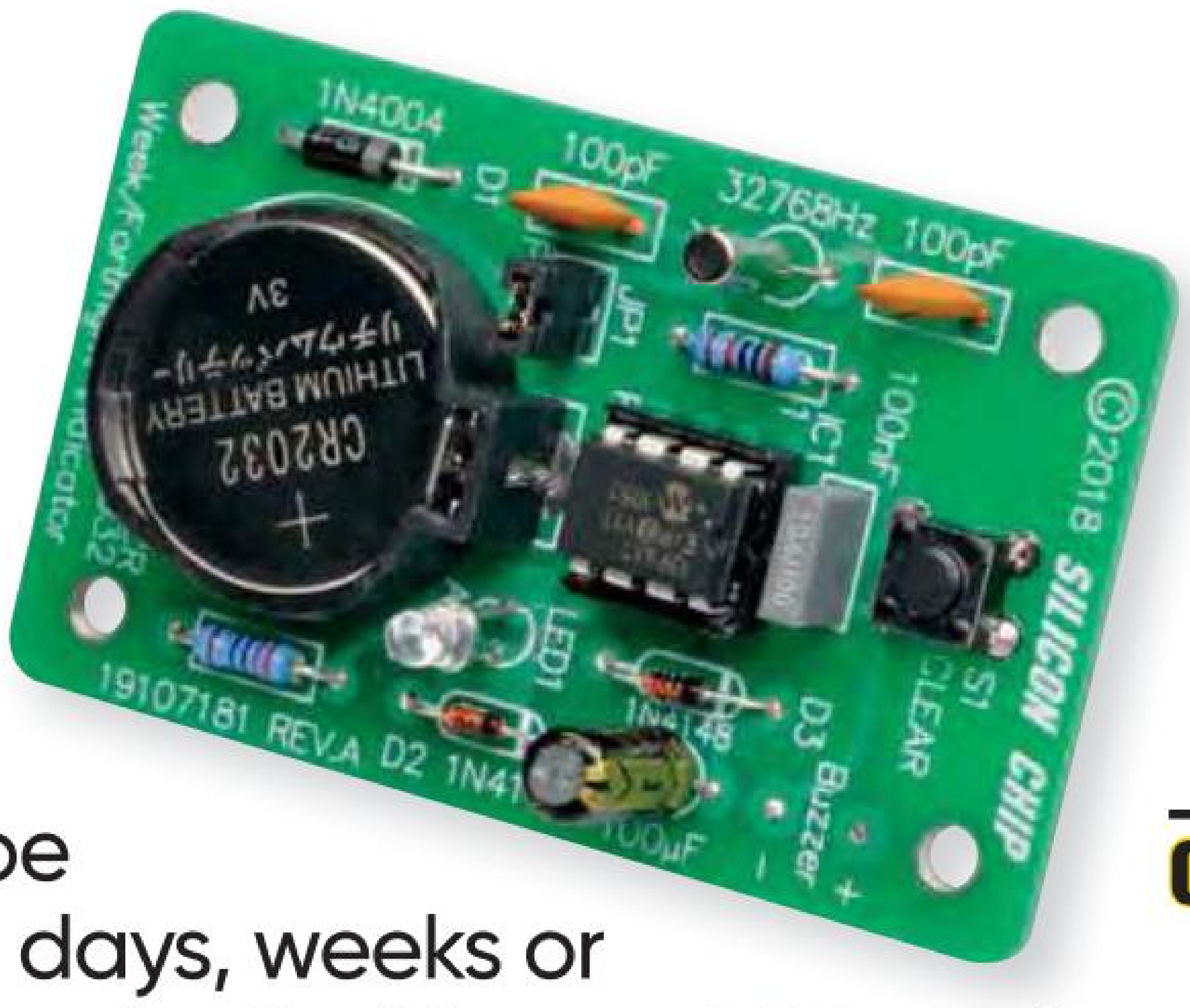
Ed Rees and Cliff Harvey

They won a PICkit 4 worth £36.75

Recurring Event Reminder

By John Clarke

Bad memory? Forget to feed and water the pets every day? This simple circuit will remind you to perform any regular task, which needs to be done every few hours, days, weeks or fortnights. It reminds you by flashing an LED, and you can even connect a piezo siren for a more insistent reminder.



REMINDER PERIOD
6, 8, 12 or 24hrs, every week or fortnight

LED REMINDER
flashes once every 2s, typically for 18hrs or until reset

AUDIBLE REMINDER
One 10ms chirp per second while the LED is flashing

POWER SUPPLY
3V lithium button cell

QUIESCENT CURRENT
19µA at 3V, 5.4µA at 2V

CURRENT WHEN LED IS FLASHING
42µA or 300µA together with piezo siren

EXPECTED CELL LIFE
1-2 years

Let's face it, any of us can (and do) forget to do important tasks which occur at regular intervals. Some examples include taking out the garbage bins, taking medication, feeding your pets or other similar daily routines.

It's especially suitable for older people who are prone to forget to check things. For example, it could be used to remind them that their pension payments have arrived in their account. Ka-ching!

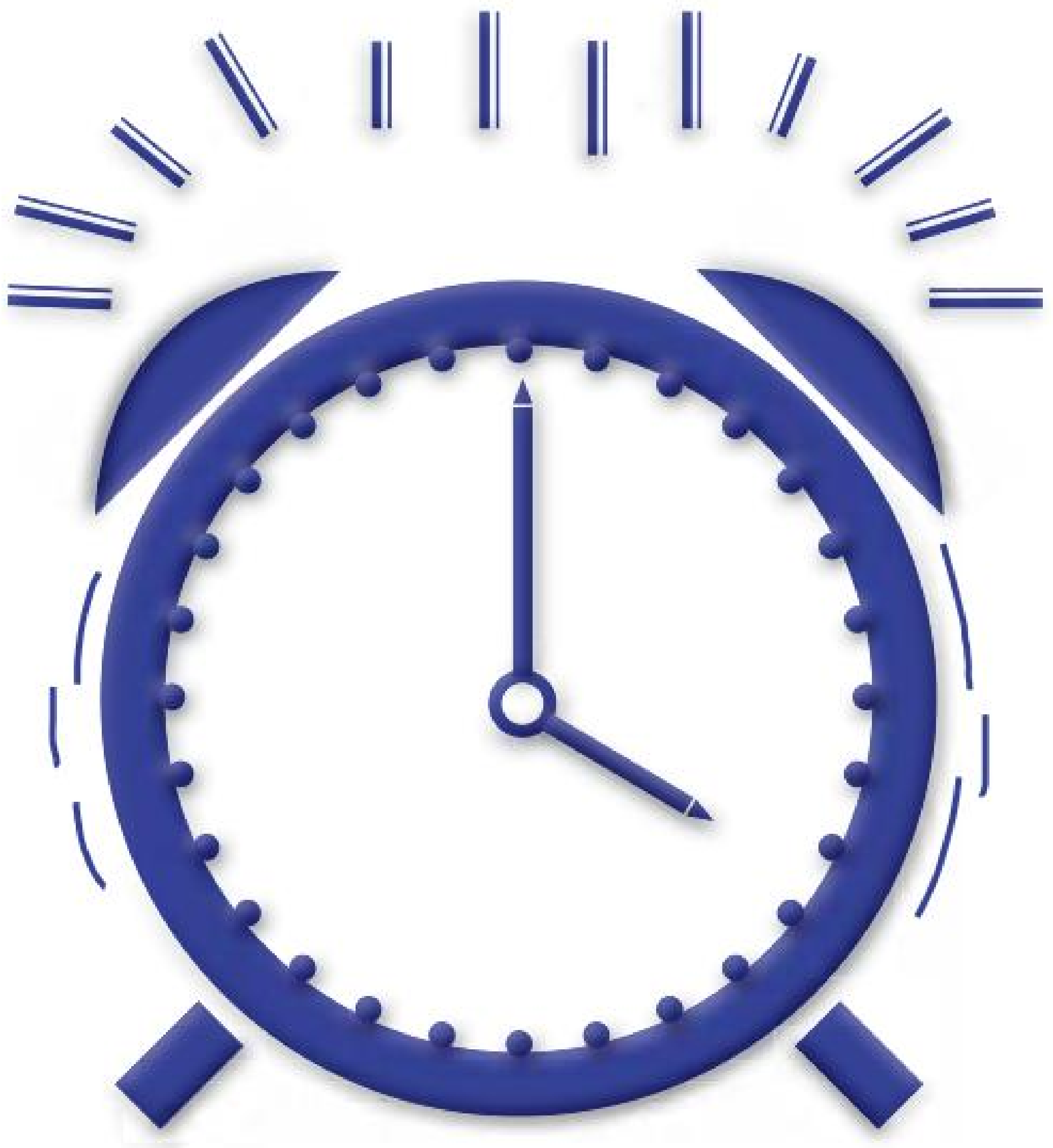
Yes, we know that you can set reminders on a smartphone, but that's just too much of a hassle for a lot of people. And if it happens to be an event that involves a member of the family, having a centralised method of reminding everyone can streamline the process.

This is a simple, low-cost unit which provides a single reminder that can be configured in a variety of ways. If you need multiple reminders, you could build more than one unit – it's certainly cheap enough.

For daily events, the *Event Reminder* has the option of either one, two, three or four regular alerts throughout the day. In other words, it can provide a reminder every 24, 12, 8 or 6 hours.

In weekly or fortnightly mode, it goes off once a week or once a fortnight. When the LED flashes to indicate the event, you can reset it by pressing a switch. Having been reset, the *Event Reminder* will then wait for the set time period before alerting you again.

Powered by a 3V button cell, the *Event Reminder* is easy to set up and we are presenting it as a bare printed circuit board (PCB) to minimise cost. Of course, you can put it in a case if you want to.



Circuit description

As shown in Fig.1, the circuit is built around an 8-pin PIC12F617 microcontroller, IC1. It uses its internal 4MHz oscillator to generate the instruction clock but there is also a 32768Hz watch crystal (X1) connected between pins 2 and 3, to run a secondary oscillator for its internal Timer 1 counter. This is used to keep track of the passage of time for the reminders.

The two 100pF capacitors at pins 2 and 3 are required to make the circuit resonant, so it can be driven by the oscillator amplifier within IC1. The crystal provides good accuracy, to within a few minutes per year.

The 3V supply is marginal for lighting a LED, especially given that the cell voltage can drop to around 2V at the end of its life. To solve that problem, the components connected between pins 6 and 7 provide a boosted supply voltage for driving LED1.

In effect, we have a diode pump: with pin 7 low and pin 6 high, the 100µF capacitor charges up to around 2.3V via diode D2.

Then, when the micro drives pin 7 high and pin 6 low, this 2.3V is added to the 3V at pin 7 to give 5.3V for driving the LED. The drive current passes through a 220Ω current-limiting resistor and LED1, back to pin 6.

Diode D3 prevents the 100µF capacitor from being reverse charged at the end of this process.

The optional piezo siren is connected between pin 6 and ground, so that when pin 6 goes high to charge the 100µF capacitor, it also powers the piezo siren, generating a brief but loud chirp.

We've elected to use a pulsating tone piezo siren, which generates its own

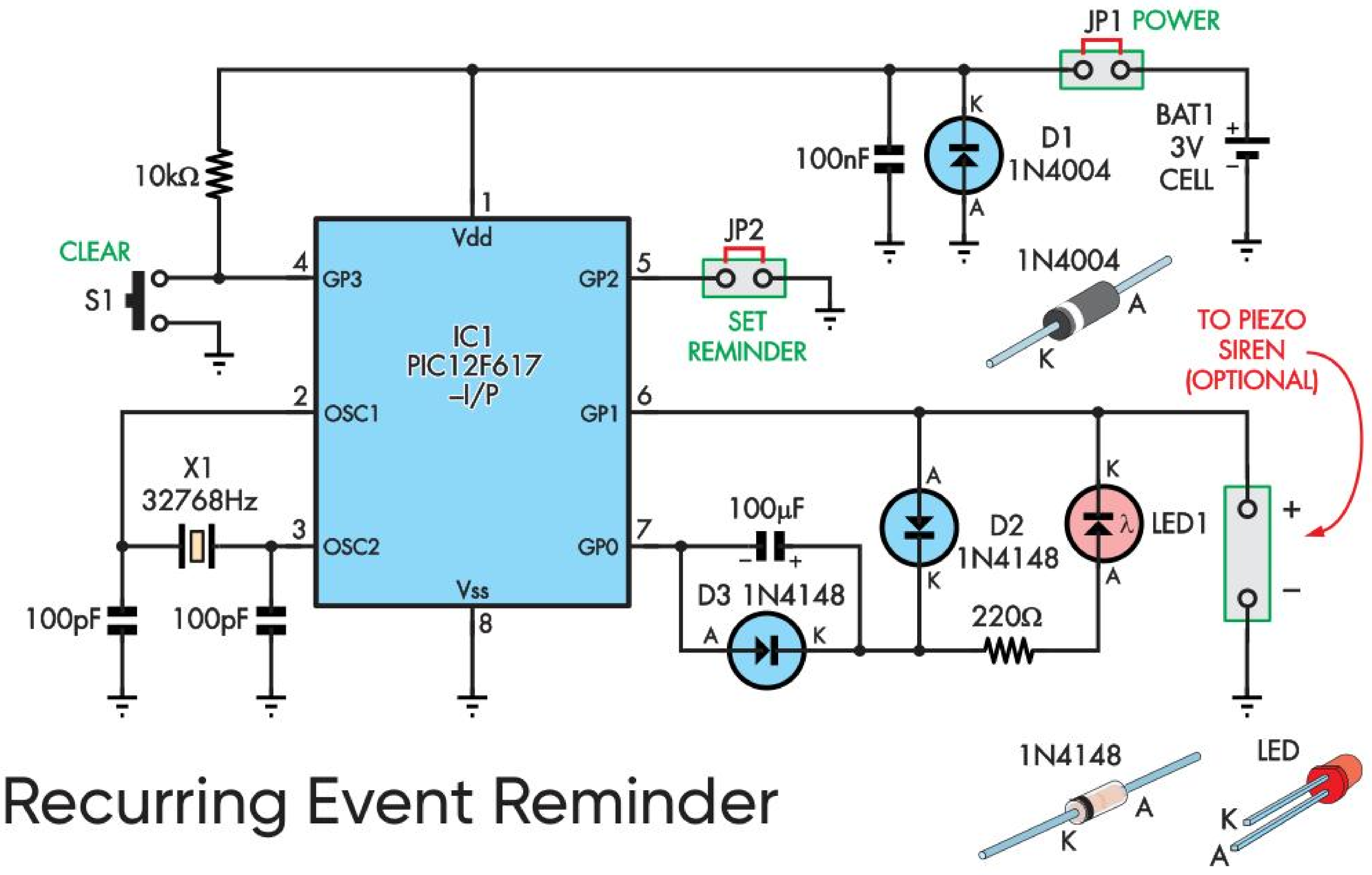

JP1 POWER
10kΩ
CLEAR
S1
4
GP3
1
Vdd
IC1
PIC12F617
–I/P
5
GP2
JP2
SET
REMINDER
100nF
K
D1
1N4004
A
BAT1
3V
CELL
+
1N4004
A
K
TO PIEZO
SIREN
(OPTIONAL)
2
OSC1
6
GP1
X1
32768Hz
3
OSC2
7
GP0
100µF
+
A
K
D2
1N4148
K
A
LED1
λ
+
–
D3 1N4148
A
K
220Ω
Vss
8
100pF
100pF
Recurring Event Reminder
1N4148
A
K
LED
K
A

Fig.1: complete circuit diagram for the *Recurring Event Reminder*. The components at pin 6 and 7 boost the 3V supply to drive the LED.

short bursts of sound since it makes our circuit simpler.

Because this type of siren does not make any sound for about half a second after power is applied, after which it emits a short burst, we keep pin 6 high for around one second, to ensure the siren sounds, even though the 100µF capacitor charges in a much shorter time.

The unit is powered by a 3V lithium cell in a holder, labelled BAT1. Jumper JP1 is used as a power switch and diode D1 provides reverse polarity protection.

If the cell is inserted incorrectly, the diode will conduct and restrict the supply voltage for IC1 to around –0.6V. The cell holder we use does not connect to the cell if it is inserted the wrong way, so this is a 'belts and braces' measure.

Maximising battery life

Most of the time, IC1 is in sleep mode, with the program halted and the internal 4MHz oscillator stopped but the 32768Hz oscillator running.

It is 'woken up' once per second, to update its internal time and date and to flash the reminder LED if necessary. Sleep mode reduces the power consumption of IC1 to a very low level (around 7µA), to maximise the life of the cell.

Switch S1 has a 10kΩ pull-up resistor that holds input pin 4 (GP3) high unless S1 is pressed. When it is pressed and pin 4 goes low, IC1 is woken from sleep to respond. S1 is used to either clear the LED flashing indication (with a short press) or reset the timer if the switch is held closed for an extended period.

Note that if the optional piezo siren is used, cell life will be slightly worse. Typically, you will not leave the piezo beeping for a long time; you would reset the reminder by pressing S1. Once the piezo stops, it will no longer be an additional drain on the cell.

Jumper JP2 is used to select weekly, fortnightly or daily reminders. When power is first applied to the circuit, the GP2 input (pin 5) is set as an input with a pull-up current applied.

If JP2 is not shorted then this input will be pulled high and the software produces weekly or fortnightly reminders. If JP2 is bridged, the GP2 input will be held low and daily reminders are produced (see panel).

The internal pull-up current is switched off shortly after initial power-up and the GP2 input is then set as a low output to reduce the supply current and extend cell life. The selection between weekly/fortnightly or the various different daily reminder periods is made by a different method, as described below.

Assembling the board

The *Event Reminder* is built on a PCB coded 19107181, measuring 62.5 × 38.5mm, and which can be ordered from the *PE PCB Service*. It is presented as a bare PCB that can sit flat, be hung or otherwise attached to a cupboard or refrigerator, or mounted in a case.

If mounting in a case, before assembling the board, you can use the PCB as a template to mark the locations to drill the four corner mounting holes in the lid, along with holes for S1 and LED1.

Use the PCB overlay diagram, in Fig.2, to assemble the board. Begin by installing the resistors. Use a multimeter to check the value of each before inserting into the PCB.

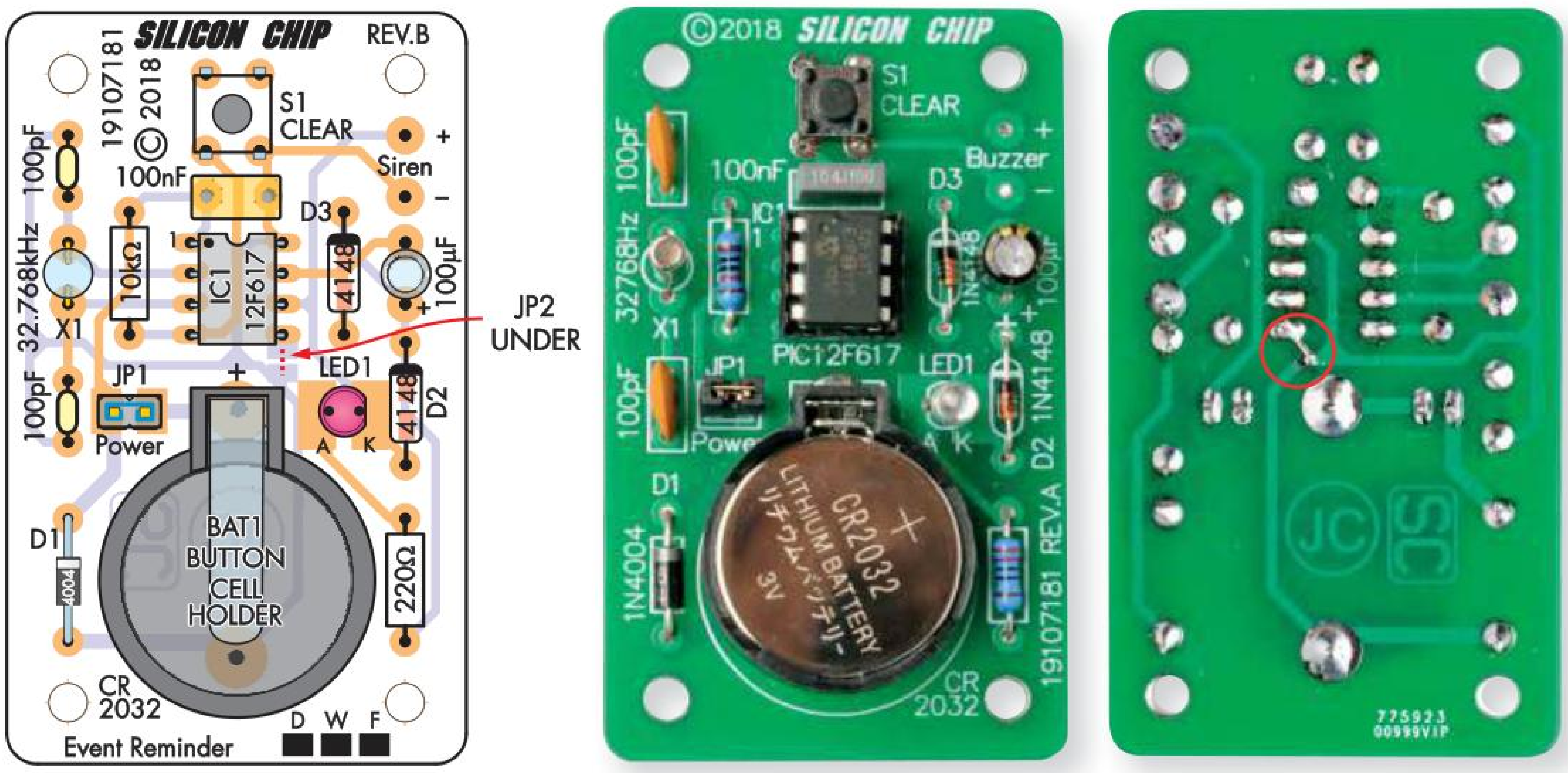
For a reminder period of 24 hours or less, the two pads on the underside of the PCB labelled JP2 need to be bridged with solder or with a short length of tinned wire. This can be a lead off-cut from one of the resistors.

Diodes D1 to D3 can be installed next, taking care to orient them correctly and noting that D1 is the 1N4004 and the remaining diodes are 1N4148s. Then fit pushbutton S1, crystal X1 and the socket for IC1. Ensure that the notched end of the socket is oriented as shown in Fig.2.

Take care when soldering the crystal as the leads are very fine and it can be damaged by excessive heating. Then mount the 100nF and 100pF capacitors – these are not polarised.

Follow with the 100µF electrolytic capacitor, ensuring that its positive (longer) lead goes through the pad

Fig.2: overlay diagram for the *Recurring Event Reminder* with the completed PCB shown. Note the orientation of the battery holder and the location of JP2 marked in red. A wire link has been used to bridge JP2 on the prototype PCB. The production board has a pair of closely-spaced pads in the same location which can be easily bridged with solder.


19107181
© 2018
SILICON CHIP
REV.B
S1
CLEAR
+
Siren
–
100nF
100pF
32.768kHz
X1
10kΩ
IC1
12F617
D3
4148
100µF
+
JP2
UNDER
JP1
Power
+
LED1
A
K
4148
D2
100pF
BAT1
BUTTON
CELL
HOLDER
D1
4004
220Ω
CR
2032
D W F
Event Reminder
©2018 SILICON CHIP
Buzzer
PIC12F617
CR2032
LITHIUM BATTERY
3V
19107181 REV.A
1N4004
CR
2032

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How to set the Recurring Event Timer

First of all, you need to decide which event reminder you want. The choices are once fortnightly, weekly, daily, or every twelve hours, eight hours or six hours each day. Changing to a different timer is simply a matter of following the instructions for that timer – otherwise, it will stay as set until changed.

Setting and resetting the timers is achieved by shorting either or both JP1 and JP2, in conjunction with reset switch S1. All setting data is stored in Flash memory, so unless you want to change the mode, you will not have to reset it when you go to use it. However, the unit's time counter is reset to zero at power up (JP1 shorted). When powered up (JP1 inserted) and S1 isn't pressed, LED1 will flash the current setting (eg, once for weekly; twice for fortnightly).

Weekly reminder
(exactly 7 days)

This is the first default mode, **without** JP2 shorted. When powered up (jumper on JP1) LED1 will flash once. LED1 will then flash exactly 7 days later from this time (to the minute!) and remain flashing for 18 hours, until reset with a short press of S1.

Fortnightly reminder
(exactly 14 days)

Without JP2 shorted, remove the shorting block from JP1, press and hold S1 while replacing the shorting block on JP1. LED1 will flash twice and you can release S1. It will start flashing exactly 14 days later and is cancelled by pressing S1 (or waiting 18 hours!). Repeating this method will reset the Event Reminder to a weekly reminder.

Daily reminder
(24 hours)

With JP2 shorted, the unit is in default daily mode. Exactly 24 hours after turning on, LED1 will flash for 18 hours, if it is not cancelled first (by pressing S1). It then repeats this process every 24 hours.

With JP2 shorted, remove JP1. Hold down S1, replace JP1 and wait for LED1 to flash twice.

Two times/day
(12 hours)

Exactly 12 hours later LED1 will flash for 8 hours, if it is not cancelled by pressing S1.

It repeats this process every 12 hours.

With JP2 shorted, remove JP1. Hold down S1, replace JP1 and wait for LED1 to flash thrice.

Three times/day
reminder (8 hours)

Exactly 8 hours later LED1 will flash for 6 hours, if it is not cancelled by pressing S1.

It repeats the process every 8 hours.

Four times/day
reminder (6 hours)

With JP2 shorted, remove JP1. Hold down S1, replace JP1 and wait for LED1 to flash four times. Exactly 6 hours later LED1 will flash for 4 hours, if it is not cancelled by pressing S1. It repeats the process every 6 hours. Repeating this method will reset it back to a daily reminder.

Set timer back to zero

Press and hold S1 for 5 seconds until LED1 starts continuously flashing. This will trigger the alarm and reset the time counter to zero. Future reminders will then be related to this time.

Be careful not to short any of the connections on the underside of the board with your finger.

marked + on the PCB. The striped side of the can indicates the negative lead.

The two-way pin header for JP1 can then be installed. Follow by fitting PC stakes at the wiring points for the piezo siren, if you plan to use one. Next, mount the cell holder, making sure its positive terminal (the release lever) is facing towards IC1.

If you are planning to mount the unit in a UB3 Jiffy box, use a tactile push-button switch with a long shaft for S1 so that it will protrude through the lid.

The board can be mounted on the underside of the lid, using four 12mm tapped spacers and eight short machine screws.

LED1 should be soldered to the PCB with its lens around 10mm above the top surface, although you could mount it higher if you wanted to. The longer anode lead must be soldered to the pad marked 'A'.

Programming the micro

Check your construction before inserting the programmed microcontroller (IC1) in its socket. Its pin 1 dot needs to be located near the notch in the socket.

If you intend to program the PIC yourself, the HEX file (**1910718A.hex**) is available from the July 2019 issue's page on the *PE* website.

Since we are using pin 4 of IC1 as an input for sensing the state of switch S1, its $\overline{\text{MCLR}}$ function is disabled. Also, we are running the chip off its internal oscillator. Some programmers do not support programming a chip in this configuration.

If you're using a PICkit 3 and MPLAB IDE/IPE to program this chip, it will produce a warning but you can ignore that warning and continue to program the chip.

With IC1 in place, fit the CR2032 cell in its holder and place a shorting block on the header marked JP1. If all is well, LED1 will momentarily flash after about one second to acknowledge that the circuit is operating.

Finishing it up

The final *Recurring Event Reminder* PCB design has three white boxes at the bottom, labelled 'D', 'W' and 'F'. These are intended to indicate whether your unit is set up for daily, weekly or fortnightly reminders respectively. You can mark the appropriate box with a pen.

If using the piezo siren, connect its black wire to the 'Buzzer –' connection on the PCB and the yellow intermittent wire (for the Jaycar unit) or red wire (for the Altronics unit) to the 'Buzzer +' terminal on the PCB.

The piezo siren will not chirp on the initial power-up indications of the LED; it only sounds during reminder alerts. If mounting it in a separate box, you can solder its wires to a two-core extension cable to connect to the *Event Reminder* PCB (as pictured above).

For our prototype, we mounted the piezo siren in a separate UB3 Jiffy box, poking out through a 25mm hole drilled in the base. You could mount the main board on the lid of the same box, or mount them separately and run a cable between the two.

Really though, there's nothing stopping you from using the unit as a bare board. This also makes it easy to change the cell, although you shouldn't need to do that very often.

For example, you could affix the board to the side of a refrigerator using Blu Tack or a similar putty-like substance at each corner.

Or you could use double-sided, foam-cored tape. Just make sure that if there is exposed metal on the fridge (eg, if it's made of stainless steel) that

Parts List – Recurring Event Reminder

1 double-sided PCB coded 19107181, 38.5 x 62.5mm (available from the PE PCB Service on page 78)
1 PCB-mount vertical tactile pushbutton switch with 6mm actuator (S1) ♦ [Jaycar SP0603, Altronics S1421]
1 20mm button cell holder (BAT1) [Jaycar PH9238, Altronics S5056]
1 CR2032 lithium cell (BAT1) [Jaycar SB2944, Altronics S4999B]
1 8-pin DIL IC socket (for IC1)
1 32768Hz watch crystal (X1) [Altronics V1902]
1 2-pin header with 2.54mm spacing (JP1)
1 jumper shunt (JP1) [Jaycar HM3240, Altronics P5450]

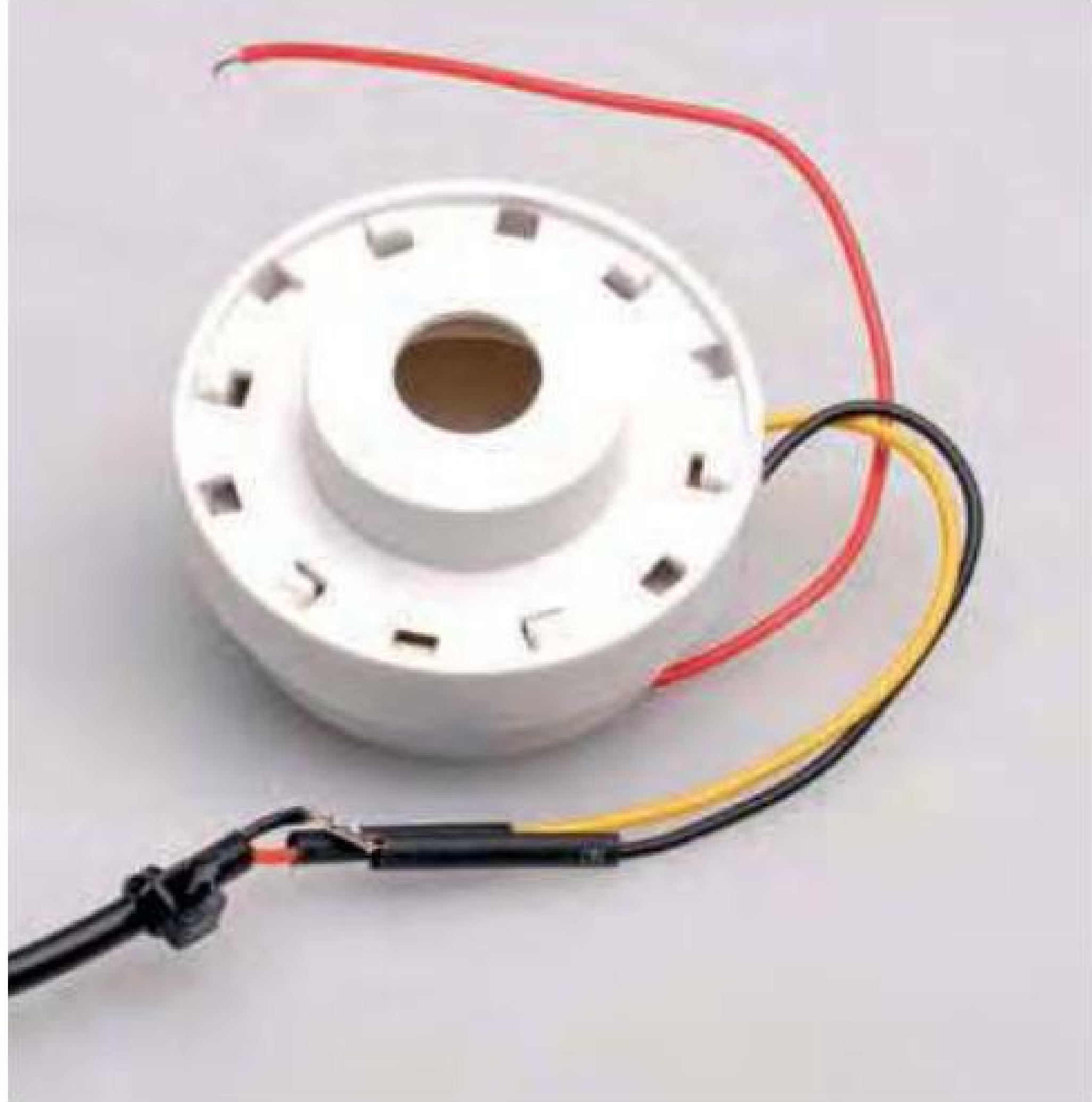
Extra parts for piezo siren
1 1-13V pulsating tone piezo siren [Jaycar AB3456, Altronics S6117]
2 PC stakes (for wiring up piezo siren)
1 UB3 plastic Jiffy box, 83 × 54 × 30mm [Jaycar HB6024, Altronics H0153]

Extra parts for mounting in case
1 UB3 plastic Jiffy box, 83 × 54 × 30mm
8 M3 x 6mm machine screws
4 12mm M3 tapped nylon spacers

Semiconductors
1 PIC12F617-I/P microcontroller programmed with 1910718A.hex (IC1)
1 1N4004 1A diode (D1) [Jaycar ZR1004, Altronics Z0109]
2 1N4148 diodes (D2,D3) [Jaycar ZR1100, Altronics Z0101]
1 3mm red high-brightness LED (LED1)

Capacitors
1 100µF 16V PC electrolytic [Jaycar RE6130, Altronics R5123]
1 100nF 50/63/100V MKT polyester or multi-layer ceramic [Jaycar RM7125, Altronics R3025B]
2 100pF C0G/NP0 ceramic [Jaycar RC5324, Altronics R2822]

Resistors (0.25W, 1%)
1 10kΩ
1 220Ω
♦ use a longer actuator version (eg, Altronics S1119) when in a UB3 case



The yellow (+) and black (–) wires of the Jaycar piezo siren output a pulsed tone, or you can connect the red and black wires for a continuous tone.

the solder joints on the underside of the board won't be shorted out.

You could also glue magnets onto the underside of the PCB and use those to hold it on the fridge. Alternatively, hang the PCB vertically on a picture frame hook, nail or screw attached to a wall.

The important point is that it should be mounted somewhere that you and your family members will regularly spend time (eg, the kitchen) so that someone will notice the flashing LED and/or noise from the siren.

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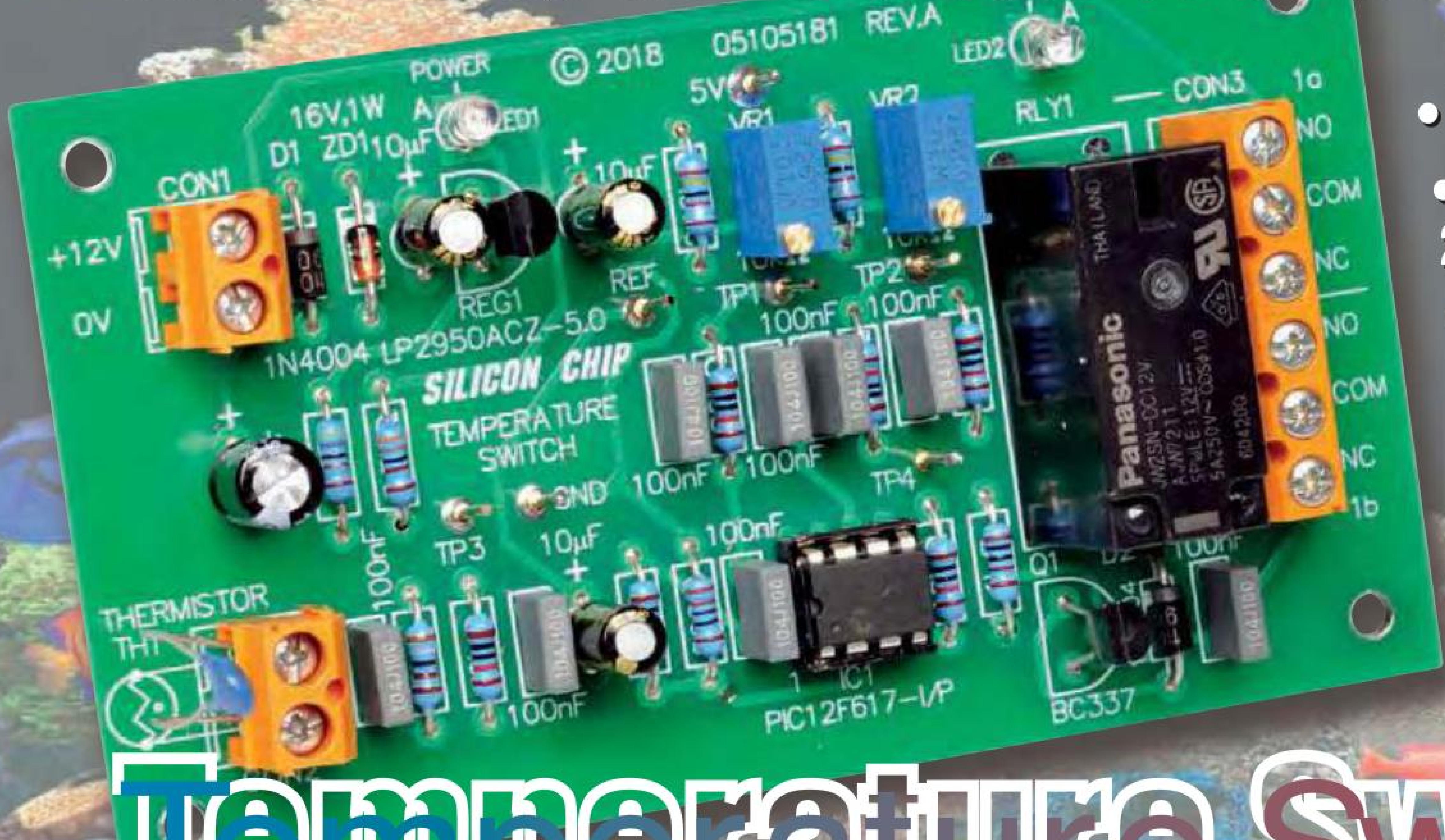
SWITCH ON OR OFF WHEN IT IS TOO HOT OR TOO COLD



- Monitors from –10°C to +125°C
- Resolution: 1°C up to 100°C; 2°C for 100-125°C
- Adjustable hysteresis
- Accuracy: typically ±2°C
- Two sets of relay contacts to control two individual devices

By John Clarke

Temperature Switch Mk2

Turn on a pump or fan if something is too hot... or turn on a heater if it's too cold. Two sets of changeover contacts allow a flexible switching arrangement. All you need to set it up is a multimeter.

There are many instances where you may want to switch something on or off at a certain temperature. You could be switching a fan, pump, light, alarm, heater, cooler or something else. Our new *Temperature Switch Mk2* can do any of these tasks. You can use it in automotive, household and industrial applications.

If switching the load directly, the *Temperature Switch* can be used for devices that have a supply voltage up to 30V DC or AC, and draw up to 5A (or 8A if the specified Altronics relay is used).

If you want to switch mains-powered devices you will need a separate 250VAC-rated relay, contactor or solid state relay.

The *Temperature Switch's* relay can be energised when the temperature goes above (or below) a particular threshold, which is set using a trimpot (VR1). Then you can set a lower (or higher) threshold temperature with another trimpot (VR2).

Why do you need two temperature settings? In practice, if you have just one temperature setting, then the relay may switch rapidly on and off (chatter) as the temperature changes by very small amounts near your preset temperature.

The difference between the two temperature settings can be as little as 1°C, but in practice you would go for a larger difference to stop the relay from switching too frequently. In effect, these two temperature thresholds provide hysteresis for the circuit.

For example, you could set the unit to energise the relay if the sensed temperature goes above 60°C, but once it has been energised, it can be set to remain energised until the temperature drops below 55°C.

If the relay is connected to a fan, that will ensure that it runs for a minimum period before switching off, ie, the time taken to reduce the temperature by 5°C.

- Switches a relay if the temperature goes above (or below) a preset value and keeps it on until the temperature drops below (or goes above) a second preset value
- Relay contact rating of up to 30VAC/DC at 5A or 8A (see parts list)
- Adjustable hysteresis is set with an upper and lower threshold
- Switching temperature can be anywhere from –10°C to +125°C
- Power supply: 12-15V DC at up to 60mA; quiescent current 20mA
- Indicators: power on LED1, relay energised LED2
- Thermistor temperature reading between TP4 and TPREF, 10mV/°C

Sensing the temperature

We use a low-cost negative-temperature coefficient (NTC) thermistor to measure temperature. It's a two-lead device with a resistance that varies with temperature. As it gets hotter, its resistance drops. It can be attached to an object to sense its temperature (eg, a heatsink).

You can get waterproof thermistors which can be immersed in liquid, or you could waterproof a standard NTC thermistor. You can also get lug-mount NTC thermistors which can be attached to a flat surface using a screw or bolt.

Circuit description

The full circuit of the *Temperature Switch* is shown in Fig.1. It's based on IC1, an 8-pin PIC12F617 microcontroller that includes an internal analog-to-digital (ADC) converter with four multiplexed inputs and a PWM (pulse-width modulation) generator.

The NTC thermistor TH1 is connected across CON2 and it forms a voltage divider in combination with the 3.9kΩ resistor from the +5V rail. Therefore, the voltage across TH1 will drop as the temperature rises.

This voltage is stabilised by a 100nF capacitor connected across the pins of CON2 and it has more filtering provided by another RC low-pass filter

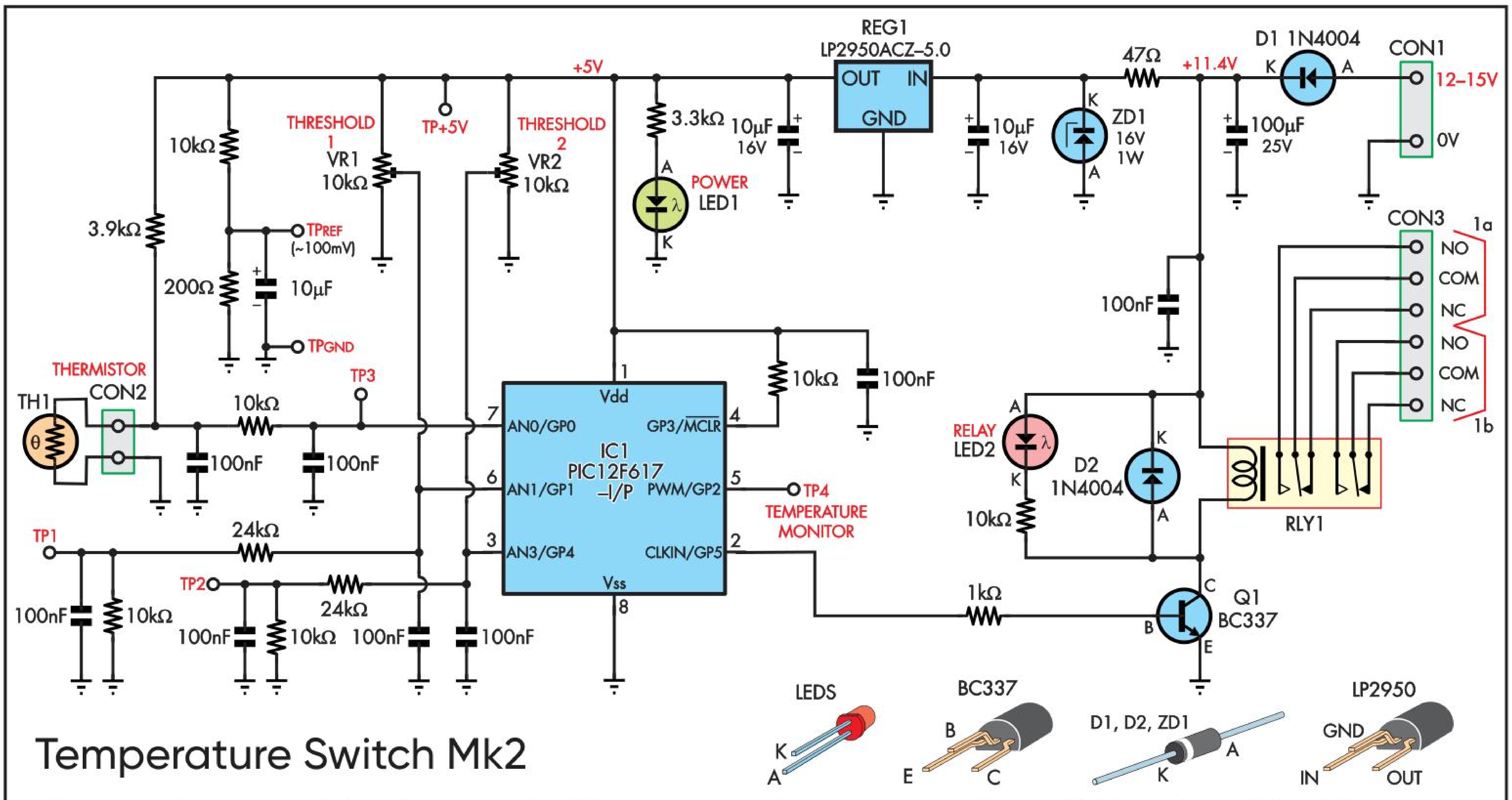

REG1
LP2950ACZ–5.0
OUT
IN
GND
+5V
47Ω
+11.4V
D1 1N4004
K
A
CON1
12–15V
0V
THRESHOLD 1
VR1
10kΩ
TP+5V
THRESHOLD 2
VR2
10kΩ
3.3kΩ
10µF
16V
POWER
LED1
10µF
16V
ZD1
16V
1W
100µF
25V
10kΩ
3.9kΩ
TPREF
(~100mV)
200Ω
10µF
TPGND
THERMISTOR
TH1
CON2
10kΩ
TP3
100nF
100nF
CON3
1a
NO
COM
NC
NO
COM
NC
1b
100nF
Vdd
AN0/GP0
GP3/MCLR
IC1
PIC12F617
–I/P
AN1/GP1
PWM/GP2
AN3/GP4
CLKIN/GP5
Vss
10kΩ
100nF
RELAY
LED2
D2
1N4004
10kΩ
RLY1
TP4
TEMPERATURE MONITOR
TP1
24kΩ
TP2
24kΩ
100nF
10kΩ
100nF
10kΩ
100nF
100nF
1kΩ
Q1
BC337
B
C
E
LEDS
K
A
BC337
B
E
C
D1, D2, ZD1
K
A
LP2950
GND
IN
OUT
Temperature Switch Mk2

Fig.1: the circuit uses a PIC microcontroller (IC1) to monitor the temperature via an NTC thermistor (TH1). IC1 compares the measured temperature to the thresholds set by trimpots VR1 and VR2 to decide when to energise RLY1.

comprising a 10kΩ resistor and second 100nF capacitor, before being fed to input pin 7 of IC1.

Pin 7 is set up as the AN0 analogue input; and IC1 can read the voltage at this pin using its internal 10-bit ADC, with a resolution of approximately 5mV (5V ÷ 2^{10}).

It then uses a look-up table to convert the voltage reading into a temperature. This is necessary since the relationship between temperature and resistance of TH1 is non-linear.

The two threshold temperatures are set using trimpots VR1 and VR2 which are connected across the 5V supply rail. Their wipers go to analogue input pins 6 (AN1) and 3 (AN3) and the setting of each potentiometer determines the voltage at these pins, ie, 0-5V. See the section below for an explanation of how these voltages correspond to temperatures.

The 100nF capacitors connected from each analogue input to ground provide a low source impedance for the ADC.

IC1 converts the voltages at pins 3 and 6 to digital values and then into temperatures. It then compares the sensor temperature to the upper and lower switching thresholds, to decide whether relay RLY1 should be energised. It drives digital output pin 2 (GP5) high to energise the relay or low to de-energise it.

When pin 2 is high, NPN transistor Q1 is turned on to energise the coil of relay RLY1, pulling in its armature and connecting the COM and NO contact pairs on CON3.

The 1kΩ base resistor sets the base current for Q1 to 4mA. LED2, connected across the coil of RLY1 via its 10kΩ series resistor, lights to show when the relay is energised.

When transistor Q1 is turned off to switch off the relay, diode D2 absorbs the voltage generated by the collapsing magnetic field in its coil. This protects Q1 from any back-EMF voltage spikes.

The DC power source is connected to CON1 and can be in the range of 12-15V DC. Diode D1 provides supply reverse-polarity protection. The voltage at D1's cathode is (nominally) around 11.4V and this is used to drive the coil of RLY1.

The 100µF electrolytic capacitor filters the supply, and voltage transients are safely clamped using a 16V zener diode (ZD1). Current through ZD1 is limited by the series 47Ω resistor.

The 3-terminal regulator (REG1) provides a regulated 5V supply rail for IC1 and TH1. LED1 is connected across the 5V supply with a 3.3kΩ current-limiting resistor and lights whenever the unit is powered up.

IC1's $\overline{\text{MCLR}}$ reset input is tied to the 5V supply via a 10kΩ resistor to provide a power-on reset for the microcontroller.

Relationship between temperature and voltage

We mentioned earlier that trimpots VR1 and VR2 can be adjusted to provide a voltage of 0-5V to IC1, corresponding to temperature thresholds that can be set in the range of –10°C to +125°C. So how do you adjust the trimpots for each temperature?

The short answer is that you connect the negative lead of your DMM (digital multimeter) to the test point marked TPREF. (It is biased to around 100mV above ground using a 10kΩ/200Ω resistive divider across the 5V supply rail). The positive lead of your DMM then goes to TP1 (for setting trimpot VR1) or TP2 (for setting VR2).

By connecting the negative lead of your DMM to TPREF, you will get a negative reading at test points TP1 and TP2 when trimpots VR1 and VR2 are set close to their fully anti-clockwise positions. This allows you to set temperature thresholds below 0°C.

The 24kΩ/10kΩ resistive dividers between AN1/AN3 and TP1/TP2 cause the voltages that you read with your multimeter at TP1 and TP2 to change by 10mV for each 1°C adjustment. So you can simply read the voltage (in mV) between TP1 and TPREF or TP2 and TPREF and then divide by ten to convert from the voltage reading to a temperature; for example, 300mV = 30.0°C, or 472mV = 47.2°C.

So the 100mV value at TPREF allows for up to a –10°C adjustment where a reading at TP1/2 will be –100mV. The maximum setting of VR1/VR2 gives a reading at the relevant test point of 1.37V (5V ÷ [24kΩ ÷ 10kΩ + 1] – 100mV) or 1370mV, corresponding to +137.0°C. This confirms that we can set the thresholds up to the +125°C maximum that the unit can handle.

We considered using a scaling factor of 1mV = 1°C, but were concerned that some DMMs may be inaccurate when reading small voltages. We were

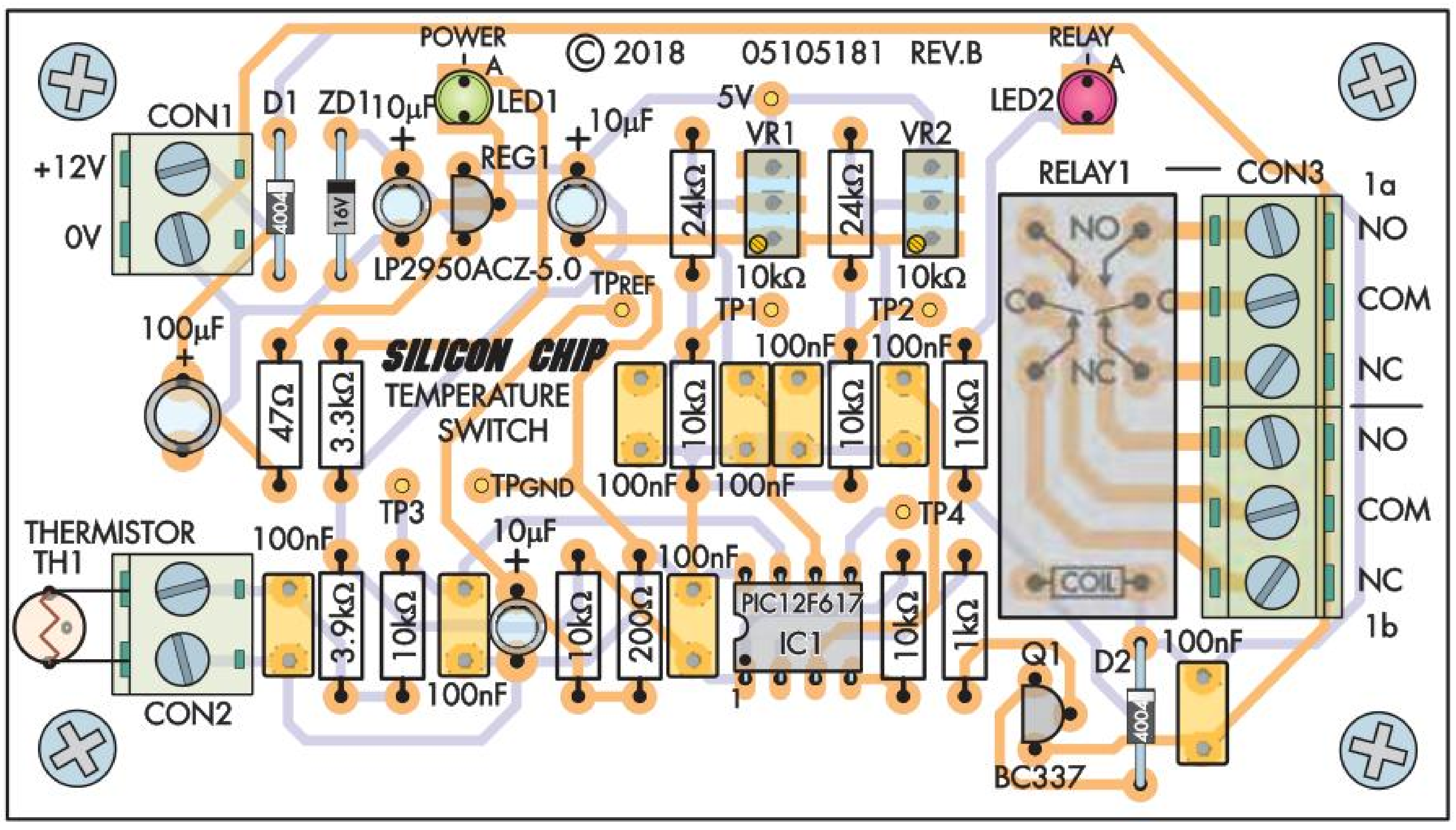
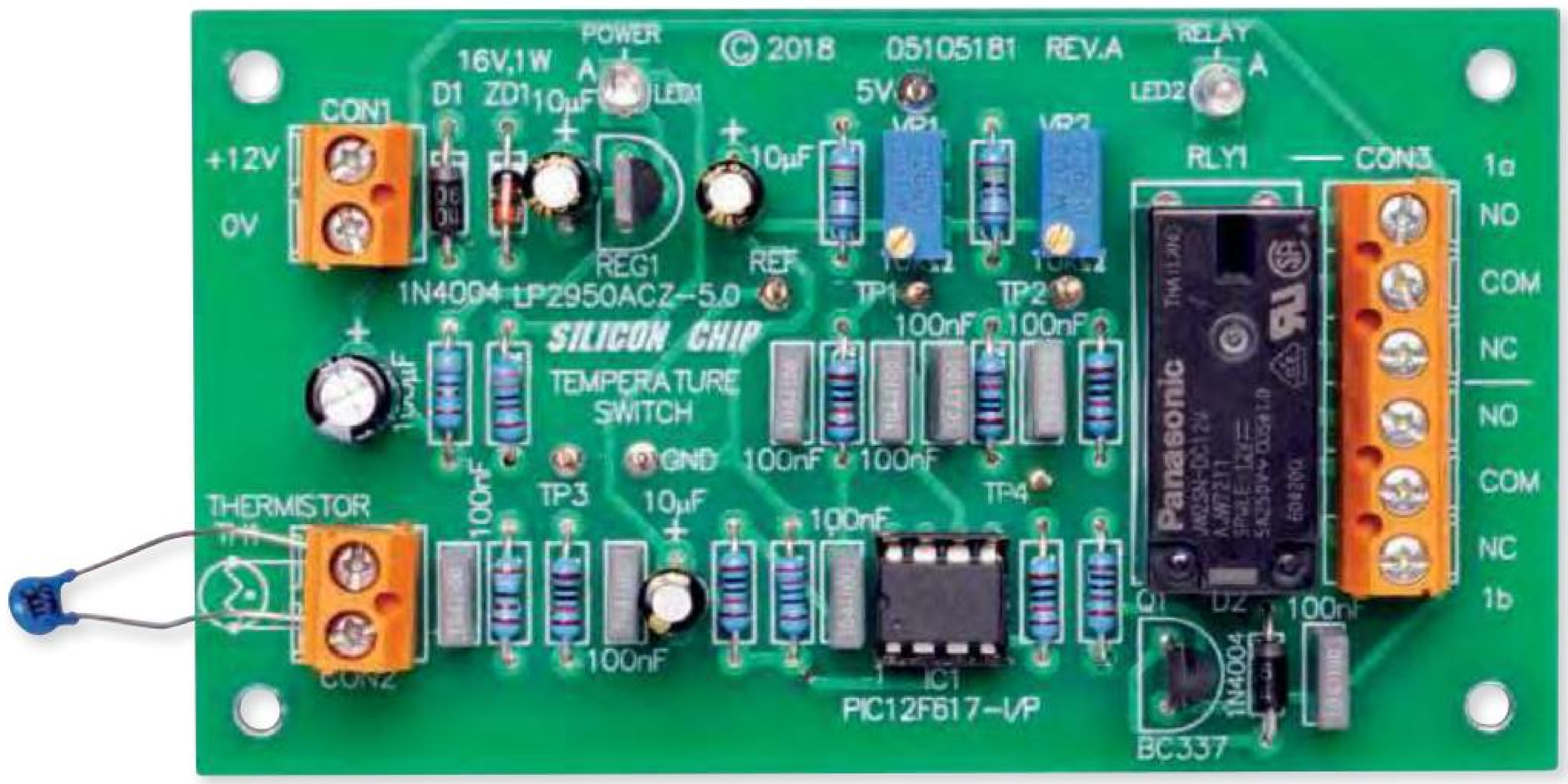


Fig.2: compare this component layout for the *Temperature Switch Mk2* with the completed prototype PCB shown below when building the project. If you need to use the *Temperature Switch Mk2* to switch on/off mains-powered devices, you have to substitute RLY1 with a 250VAC-rated DPDT relay, which must be mounted *off* the PCB.



also concerned that this could result in increased inaccuracy due to noise and EMI that could be picked up by the meter.

Note that we feed the voltage at the wipers of VR1 and VR2 directly to IC1, rather than sensing the divided-down voltages at TP1 and TP2. This allows us to use the full 10-bit resolution of IC1's ADC, giving better accuracy. The equivalent scaling is done in the software so that the temperature thresholds match the readings at TP1 and TP2.

Monitoring temperatures

So that you can monitor the current sensor temperature easily, the PWM output at pin 5 is driven with a 3.9kHz square wave with a duty cycle that is proportional to temperature. When you connect a DMM between this pin and TPREF, it will internally average out the PWM signal to give a DC voltage reading. This also has a scaling factor of 10mV/°C.

So if you get a reading of say 275mV between TP4 and TPREF, that corresponds to a temperature of 27.5°C (275mV ÷ 10mV). If you want to measure the voltage across the thermistor, you can do so between TP3 and GND.

Selecting a thermistor

The thermistor we used has a reference resistance of 10kΩ at 25°C and a beta value of 4100. 10kΩ NTC thermistors are very common, so you shouldn't have trouble finding a suitable sensor.

The beta value determines the shape of the temperature/resistance curve. While beta values vary from device to device, it is very common to find NTC thermistors with a beta close to 4000. As long as yours is in the range of 3900-4200 then it should give similar results to the one used in our prototype.

We generated the temperature lookup table for our firmware using this online calculator: **http://bit.ly/pe-jul19-ts1**

If you want higher accuracy

Although general-purpose NTC thermistors are typically accurate to within a few degrees Celsius, if you want higher accuracy, use a thermistor with tight tolerances such as the AVX NJ28NA0103FCC. This has a 1% tolerance at 25°C and a beta value of 4100, also with a 1% tolerance. It is available from RS, part 697-4578.

This thermistor is not encapsulated. For remote temperature measurement, you can extend the leads. Remeber to use use insulation sleeving (eg, heatshrink tubing) over the wire connections. For attachment to a solid object, the thermistor can be epoxy glued to the object or clamped against it. For outdoor use or immersion in liquid, insulate the thermistor assembly using neutral-cure silicone sealant.

Note that if extending the leads over long distances, even if the wires add a resistance of more than 10Ω, this is still only a 0.1% error at 25°C; although the error will increase at higher temperatures. So check the total ('round-trip') resistance before wiring the thermistor to a very long cable.

Construction

The *Temperature Switch Mk2* is built on a double-sided PCB coded 05105181 measuring 104 x 58.5mm, which can be ordered from the *PE PCB Service*. It can be housed in a UB3 129 × 68 × 43mm Jiffy box, mounted on short spacers.

Use the overlay diagram (Fig.2) as a guide during construction. Fit the resistors first. These have colour-coded bands, but we suggest that you use a DMM set to measure ohms to check the values, as the colour bands can be easily misinterpreted.

Diodes D1, D2 and ZD1 are installed next and these need to be inserted with the correct polarity, ie, with the striped end (cathode, 'k') oriented as shown in Fig.2. Both diodes are 1N4004 types, and the zener diode (ZD1) is a 1N4745 or equivalent.

We recommend using an IC socket for IC1. Take care with orientation when installing the socket and when inserting the IC. Note that IC1 needs to be programmed with the software for the Temperature Switch before use. A programmed IC can be obtained from the SILICON CHIP Online Shop (search for it by code or month).

Alternatively, you can program a blank chip yourself using the HEX file (**0510518A.HEX**) which is available from the July 2019 issue's page on the *PE* website.

At the test points we used five PC stakes for TPREF, TP1, TP2, TP3 and TP4. Plus two more for TPGND and TP+5V. If left bare, pads can be probed directly using standard DMM leads.

The capacitors are mounted next. The electrolytic types must be inserted with the polarity shown (longer lead is positive, with a stripe on the can indicating the negative lead). Install transistor Q1 and regulator REG1 now, and take care not to mix them up as they have the same package.

Now fit trimpots VR1 and VR2. They may be marked with code 103. Orient these with the adjusting screw as shown in Fig.2, toward IC1.

Install terminal blocks CON1, CON2 and CON3 now. CON1 and CON2 are 2-way types that are mounted separately while CON3 comprises two 3-way screw connectors dovetailed together. Fit all three connectors with the wire entry to the outside edge of the PCB.

Finally, the LEDs and RLY1 can be mounted. We placed the LEDs close to the PCB but they can be mounted higher or even off the PCB, for example, chassis-mounted to the case.

If mounting them off-board, wire them to the LED pads with flying leads. The LEDs must be oriented correctly with the anode (longer lead) of the LED to the pad marked 'A' on the PCB.

Although presented as a bare PCB, the *Temperature Switch* can be installed in a UB3 box. Mark out and drill the 3mm holes in the box, corresponding to the corner mounting holes on the PCB, then attach it to the box using short spacers and screws. Holes will be required at each end of the box (or on the lid) for cable glands, which the power supply, thermistor and relay wiring will pass through.

Testing

You will need a 12-15V DC supply capable of delivering up to 60mA. Connect the power supply to CON1 and the thermistor to CON2.

Leave IC1 out of its socket before switching the power supply on. LED1 should light. Now measure the voltage between TP+5V and TPGND. The reading should be between 4.975V and 5.025V. Next, check the voltage between TPREF and TPGND. It should be between 96.5mV and 99.5mV, ideally close to 98mV.

If these voltages are correct, then switch the supply off and insert IC1, taking care to orient it correctly.

Switch the power back on and measure the voltage between TP4 and TPREF. Check that this corresponds to room temperature, keeping in mind the 10mV/°C scaling factor.

To test the switching operation, connect your DMM between TP2 and TPREF, then adjust VR2 for a reading that is a few tens of millivolts above the reading at TP4. For example, if you read 220mV at TP4 (corresponding to 22°C), adjust VR2 for 260mV at TP2 (corresponding to 26°C).

Now connect your DMM between TP1 and TPREF and adjust VR1 for an intermediate reading, eg, 240mV corresponding to 24°C.

At this point, RLY1 should not be energised. Heat up the thermistor and the relay should be energised; you should hear it click and LED2 will light up. Then cool the thermistor down and it should click again as it's de-energised.

Depending on the ambient temperature, you may be able to heat up the thermistor by simply holding it between two fingers. Or you could use a cigarette lighter, with the flame briefly held below the thermistor body.

Setting the thresholds

Now determine the temperatures at which you want the relay to be energised and de-energised.

If you want the relay energised when the temperature rises above a particular threshold then this temperature becomes your upper threshold. Subtract your desired hysteresis value (in °C) from the upper threshold to determine the lower threshold.

In this case, use the same procedure described above in 'Testing' so that the voltage reading between TP1 and TPREF equals the lower threshold and the reading between TP2 and TPREF equals the desired upper threshold.

Conversely, if you want the relay to be energised when the temperature falls below a particular threshold then this will be your lower threshold and you should add the desired amount of hysteresis to it, to determine the upper threshold value.

In this case, adjust VR1 to give a reading between TP1 and TPREF equal to your upper threshold and adjust VR2 to give a reading between TP2 and TPREF that corresponds to your lower threshold.

Do not set both thresholds to the same temperature as this will cause relay chatter.

Installation

Wire your power supply leads to CON1. For use in a motor vehicle, use automotive-rated wire with the +12V terminal connected to the switched side of the ignition. That way, your battery won't be drained when the ignition switch is off.

The 0V terminal on CON1 should be connected to the vehicle chassis (assuming you have a negative chassis, like all modern vehicles) using a crimp eyelet secured to a convenient screw terminal. You may need to drill a separate hole for this connection if you can't utilise an existing earth connection.

Note that while the test points can show readings with a resolution greater than 1°C (252mV for 25.2°C) the *Temperature Switch* will only switch RLY1 on and off at the temperature settings and readings rounded *up* to the nearest degree.

Parts List

1 double-sided PCB, coded 05105181, 104 x 58.5mm (available from the PE PCB Service, page 78)
1 DPDT 12V DC coil relay (RLY1) [Jaycar SY4052 (5A) or Altronics S4270A (8A)]
1 10kΩ NTC thermistor with beta ~4100; see text (TH1) [Jaycar RN3440]
2 2-way screw terminals with 5.08mm pin spacing (CON1,CON2)
2 3-way screw terminals with 5.08mm pin spacing (CON3)
1 DIL 8-pin IC socket for IC1
7 PC stakes (optional) (TP+5V, TPGND,TP1,TP2,TP3,TP4 and TPREF)
1 UB3 jiffy box, spacers and mounting screws (optional)

Semiconductors
1 PIC12F617-I/P programmed with 0510518A.HEX (IC1)
1 LP2950ACZ-5.0 regulator (REG1)
1 BC337 NPN transistor (Q1)
1 16V 1W (1N4745) zener diode (ZD1)
2 1N4004 1A diodes (D1,D3)
2 3mm LEDs (LED1,LED2)

Capacitors
1 100µF 25V PC electrolytic
3 10µF 16V PC electrolytic
8 100nF 63/100V MKT polyester

Resistors (all 1%, 0.25W)
2 24kΩ 6 10kΩ 1 3.9kΩ
1 3.3kΩ 1 1kΩ 1 200Ω
1 47Ω
2 10kΩ multi-turn vertical trimpots (3296W style) (VR1,VR2)

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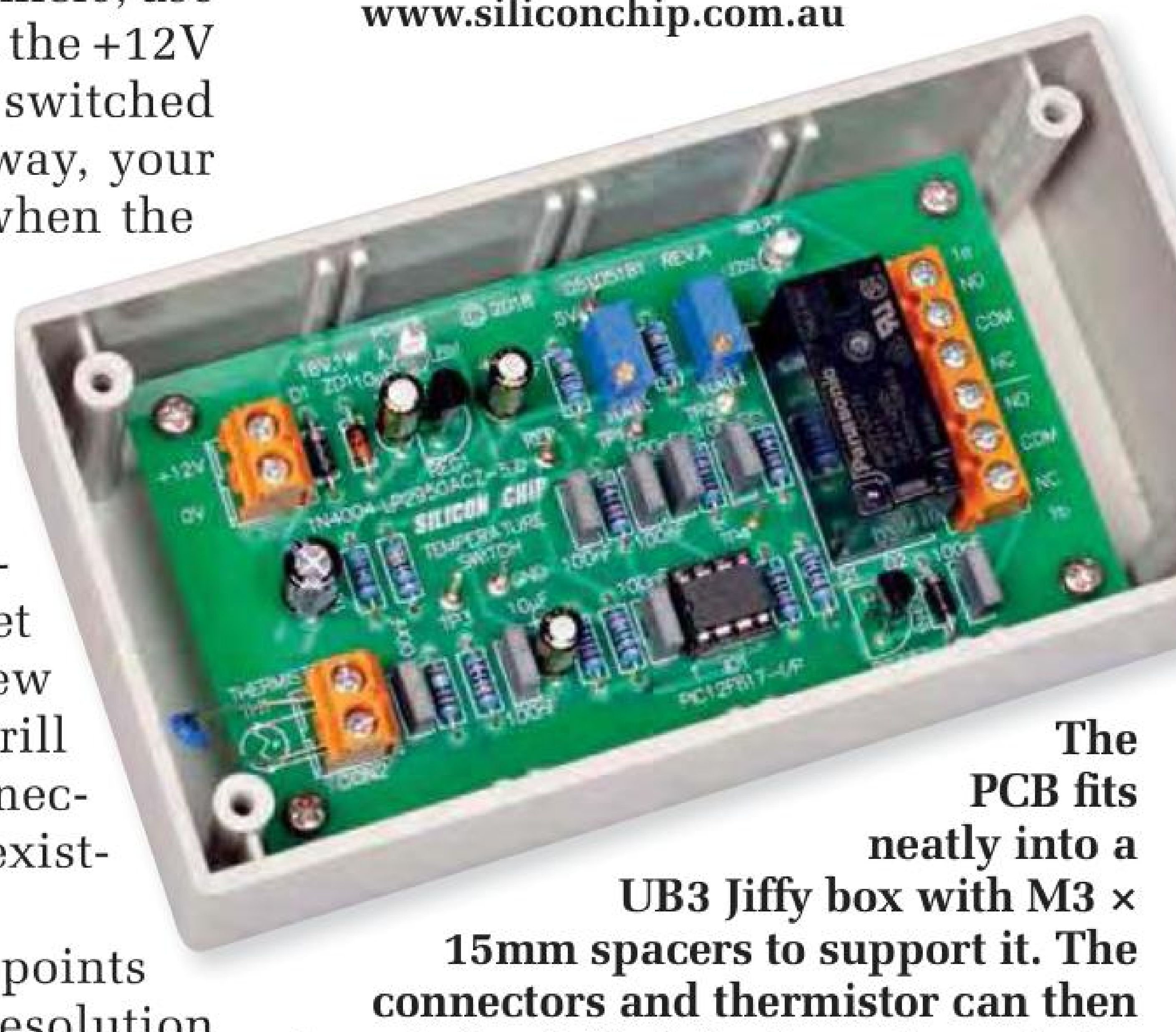
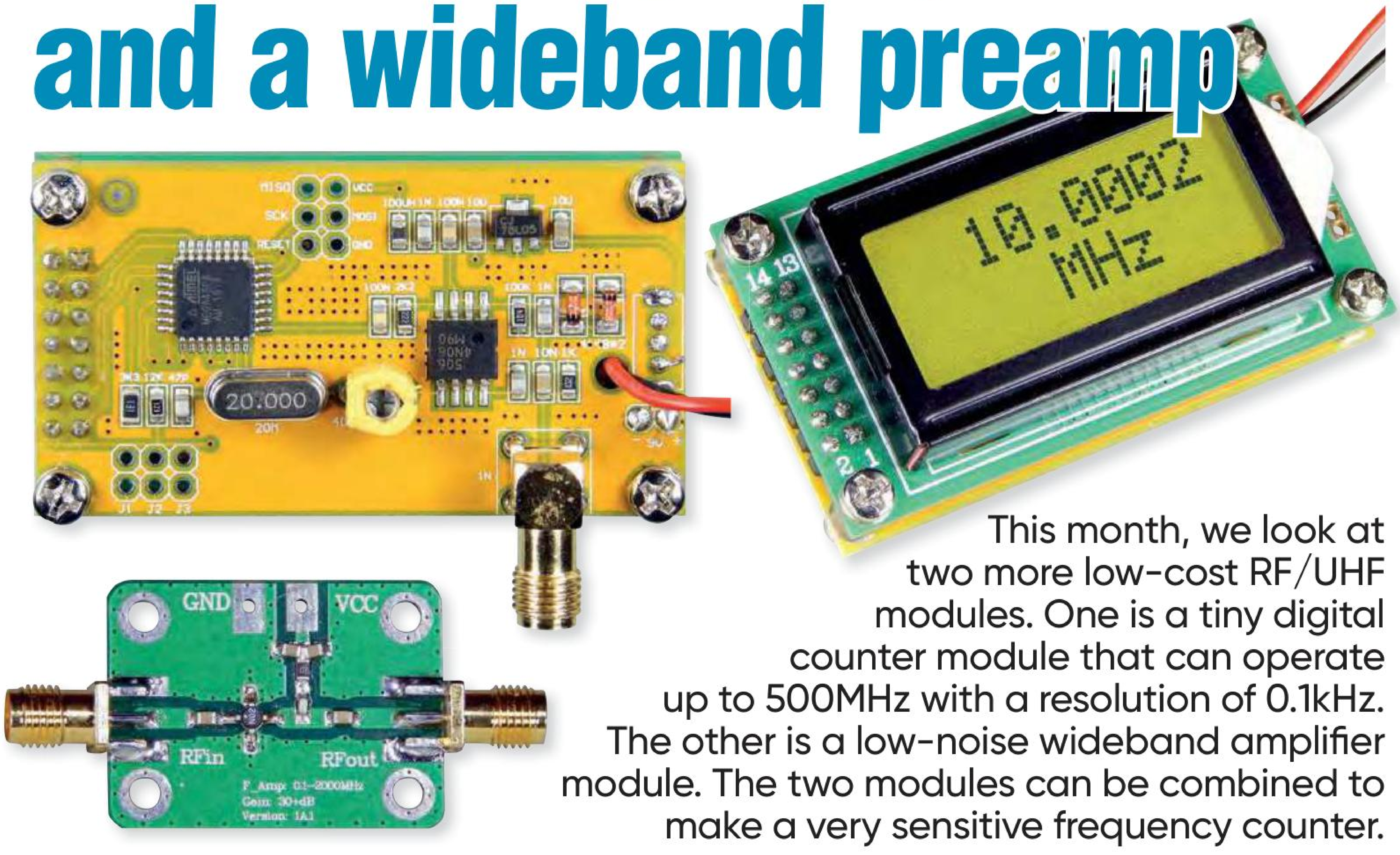


The PCB fits neatly into a UB3 Jiffy box with M3 × 15mm spacers to support it. The connectors and thermistor can then have holes drilled for them through the top of the lid or out the side of the box. Note that the PCB is slightly less wide than the typical UB3 box to account for variations and contraction of the material under strain.

Using Cheap Asian Electronic Modules Part 18: by Jim Rowe

500MHz frequency counter and a wideband preamp



This month, we look at two more low-cost RF/UHF modules. One is a tiny digital counter module that can operate up to 500MHz with a resolution of 0.1kHz. The other is a low-noise wideband amplifier module. The two modules can be combined to make a very sensitive frequency counter.

First, let's look at the 500MHz frequency counter module. It's pretty small, with the PCB measuring only 58 × 32mm; exactly the same size as the backlit 8×2 LCD display board it's mounted behind.

The whole assembly measures only 58 × 40 × 28mm, including the SMA input connector mounted on the underside of the counter PCB.

A subminiature on/off slider switch is fitted on the right-hand end of the same PCB, with the ends of a standard 9V battery clip lead attached nearby.

Before we go any further, I should note that the slider switch in the counter module turned out to be very flimsy, with the actuator falling out after being used only a couple of times. Rather than try and fix it, I removed the rest of the switch (which is why it's missing in the pictures) and used a small toggle switch off the PCB to perform the same function.

Fig.1 shows the full circuit. IC1 is an ATmega48PA microcontroller, which does most of the work. As well as doing the frequency counting, it also displays the result on the LCD module. The other IC to its left (IC2) is obviously a prescaler, but I can't find any real information on it; '5064N06' is marked on its IC package (it looks to be pin-compatible with the MB506 prescaler IC).

By measuring its input and output frequencies, I determined that it is a 64:1 prescaler, so IC1 only needs to measure frequencies up to 7.8125MHz (500MHz ÷ 64), which is well within its capabilities.

IC1 uses a 20MHz crystal (X1) for both its master clock and its counting timebase. To allow adjustment of the exact frequency for calibration of the counter, the module's designers have provided a 5-40pF trimmer cap to 'pull' its frequency.

At first, it appears that the 8×2 LCD module has no connections to its built-in LED back-lighting, but these are presumably made inside the module. There's no trimpot to adjust the LCD contrast but the default contrast seems to be fine.

There's provision on the counter PCB for a 6-pin header (shown at lower left in Fig.1) with the same connections as used for the ICSP connector on most Arduino MCUs. This would allow you to reprogram IC1 if you wish.

There's also provision on the counter PCB for three 2-pin headers for jumper shunts (J1-J3) but I haven't been able to find any information on their function.

All of the counter circuitry runs from 5V DC, derived from the 9V battery via REG1, a 78L05 regulator. The total current drain measured 57mA, much of which would be for the LCD backlight. Therefore, it would be a good idea to power it from a 9V alkaline battery or a 9V DC plugpack. You could even use a 5V USB charger with its output wired directly to the output of REG1.

Trying out the counter

I powered the module using a 9V alkaline battery and connected its input to the 10.000000MHz output from a GPS-disciplined rubidium vapour frequency standard.

Then I adjusted the frequency reading using the 5-40pF trimcap on the

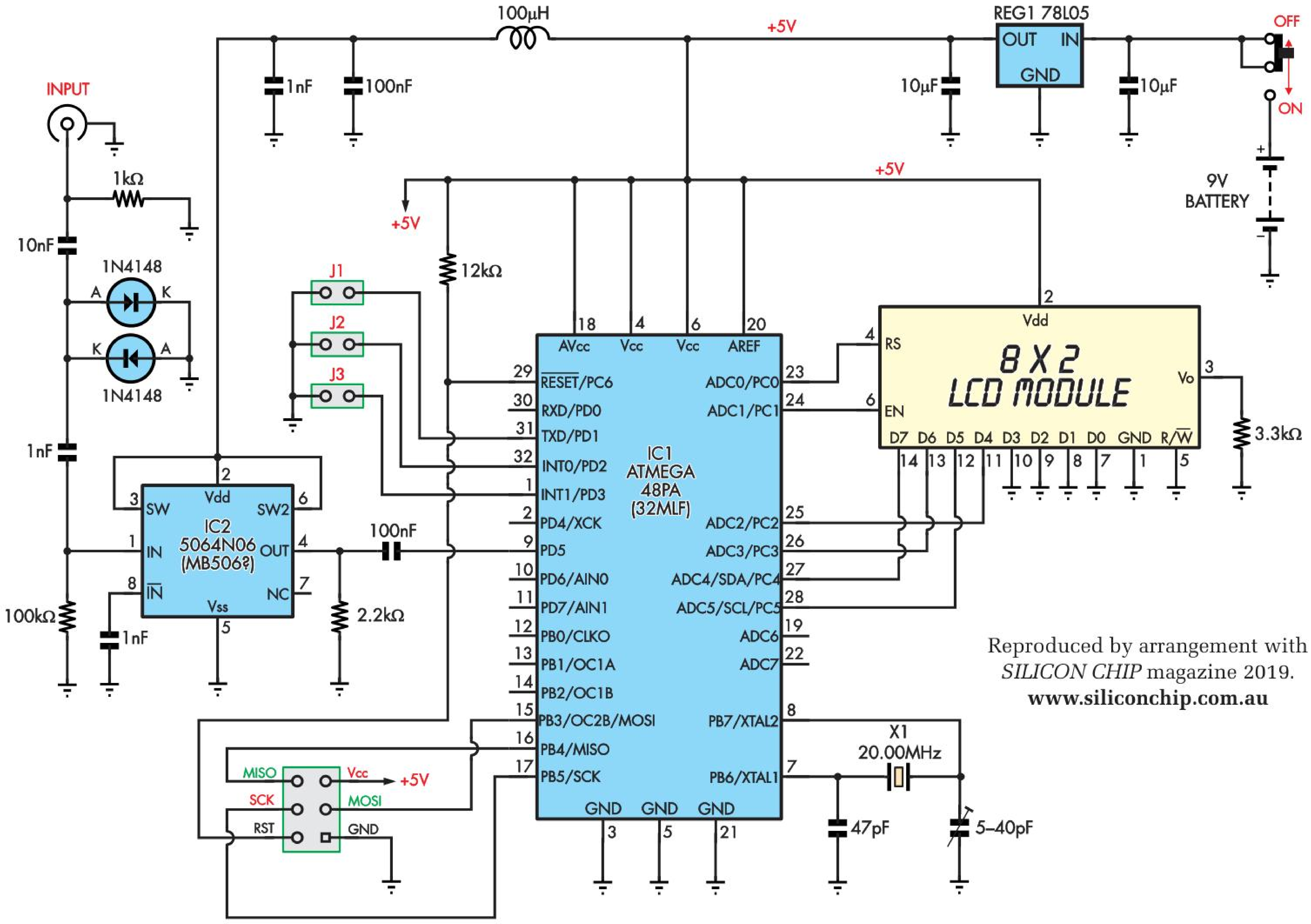

100µH
+5V
REG1 78L05
OUT
IN
GND
OFF
ON
10µF
10µF
1nF
100nF
INPUT
1kΩ
10nF
1N4148
A
K
K
A
1N4148
1nF
100kΩ
1nF
+5V
12kΩ
J1
J2
J3
9V BATTERY
IC2
5064N06
(MB506?)
Vdd
SW
SW2
IN
OUT
IN
NC
Vss
100nF
2.2kΩ
IC1
ATMEGA
48PA
(32MLF)
AVcc
Vcc
Vcc
AREF
RESET/PC6
RXD/PD0
TXD/PD1
INT0/PD2
INT1/PD3
PD4/XCK
PD5
PD6/AIN0
PD7/AIN1
PB0/CLKO
PB1/OC1A
PB2/OC1B
PB3/OC2B/MOSI
PB4/MISO
PB5/SCK
ADC0/PC0
ADC1/PC1
ADC2/PC2
ADC3/PC3
ADC4/SDA/PC4
ADC5/SCL/PC5
ADC6
ADC7
PB7/XTAL2
PB6/XTAL1
GND
GND
GND
8 X 2
LCD MODULE
Vdd
RS
EN
Vo
D7 D6 D5 D4 D3 D2 D1 D0 GND R/W
3.3kΩ
MISO
Vcc
+5V
SCK
MOSI
RST
GND
X1
20.00MHz
47pF
5–40pF

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Fig.1: IC2 is marked '5064N06' and is most likely a variant of the MB506 prescaler IC. The MB506 can divide its input frequency by 64, 128 or 256, and is set to a division ratio of 64:1 by connecting SW and SW2 to V_{DD}. The 6-pin header is not fitted, but can be installed if IC1 needs to be reprogrammed.

counter PCB. The adjustment was fairly critical and the closest reading I was able to achieve was 10.0002MHz, ie, 20ppm or 200Hz high. That's quite reasonable.

I then checked its operation over the full range of frequencies it claims to handle, using my Gratten GA1484B signal generator. With the generator's output set to 0dBm (224mV RMS), there were no problems measuring frequencies from 500MHz down to about 8MHz. For inputs below 8MHz, I did find that the signal level had to be increased somewhat to get a correct reading.

In fact, for frequencies below 3MHz I needed to crank up the generator's output to its maximum level of +13dBm (1.00V RMS); even so, I got no reading below 1MHz.

I then measured the input sensitivity for reliable readings over the range from 1MHz to 500MHz and the resulting plot is shown in Fig.2. The effective input sensitivity is below –15dBm (40mV) for all frequencies above 25MHz, falling to around –19dBm (25mV) at 500MHz. However, it rises fairly steeply at lower frequencies to reach 0dBm (224mV) at around 7.5MHz and climbs further to +13dBm (1.00V) at 3MHz.

So although the mini 500MHz counter module is claimed to be able to operate down to 100kHz, in fact its useful range is really from 1MHz to 500MHz.

I then decided to try fitting three pin headers to the pads marked JP1-JP3.

Shorting JP1 did not appear to have any effect on the readings. JP2 caused the readout to only display 0MHz.

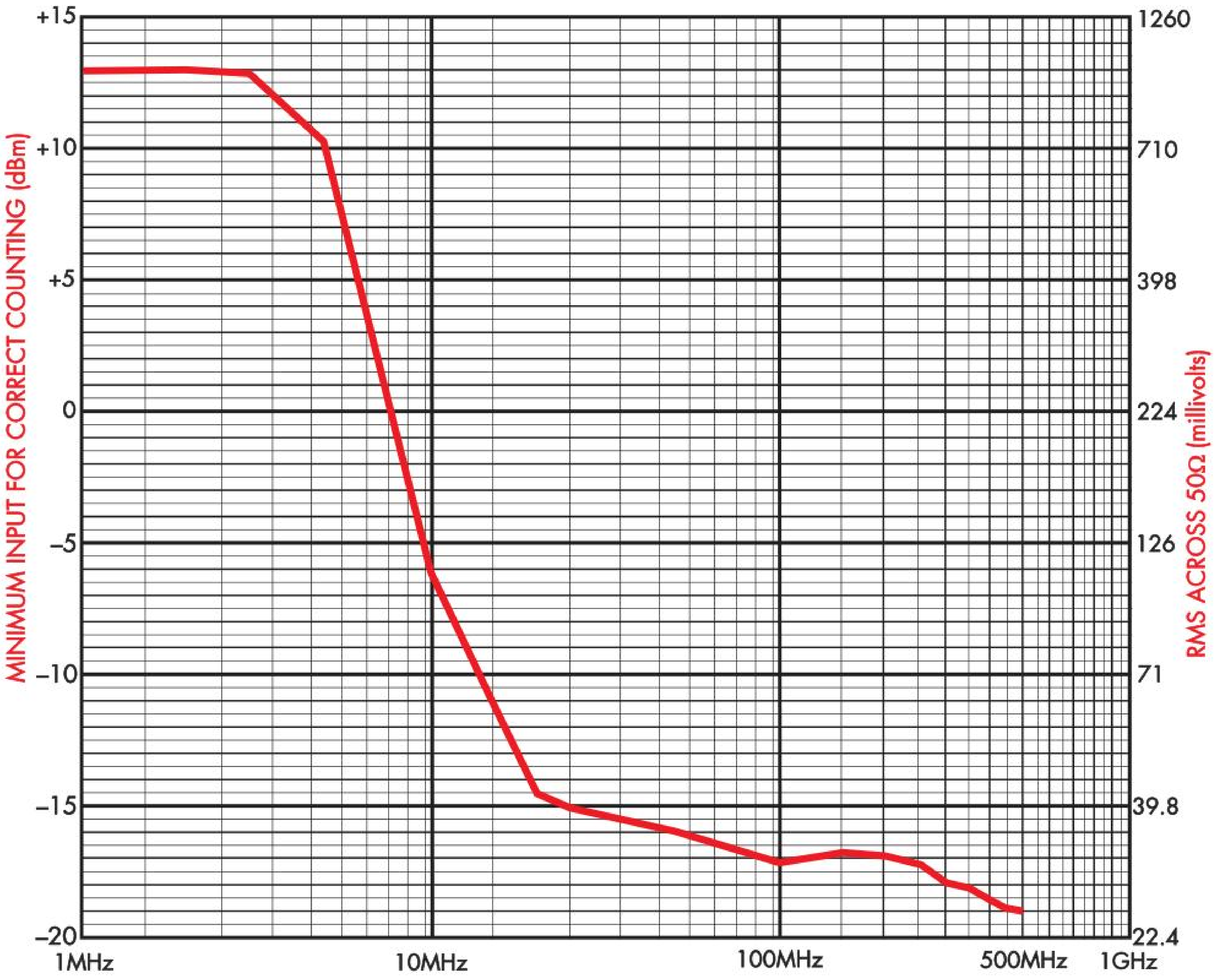


Fig.2: input sensitivity for the 500MHz frequency counter module over its full range. Below 1MHz no reading was recorded with an output level of +13dBm.

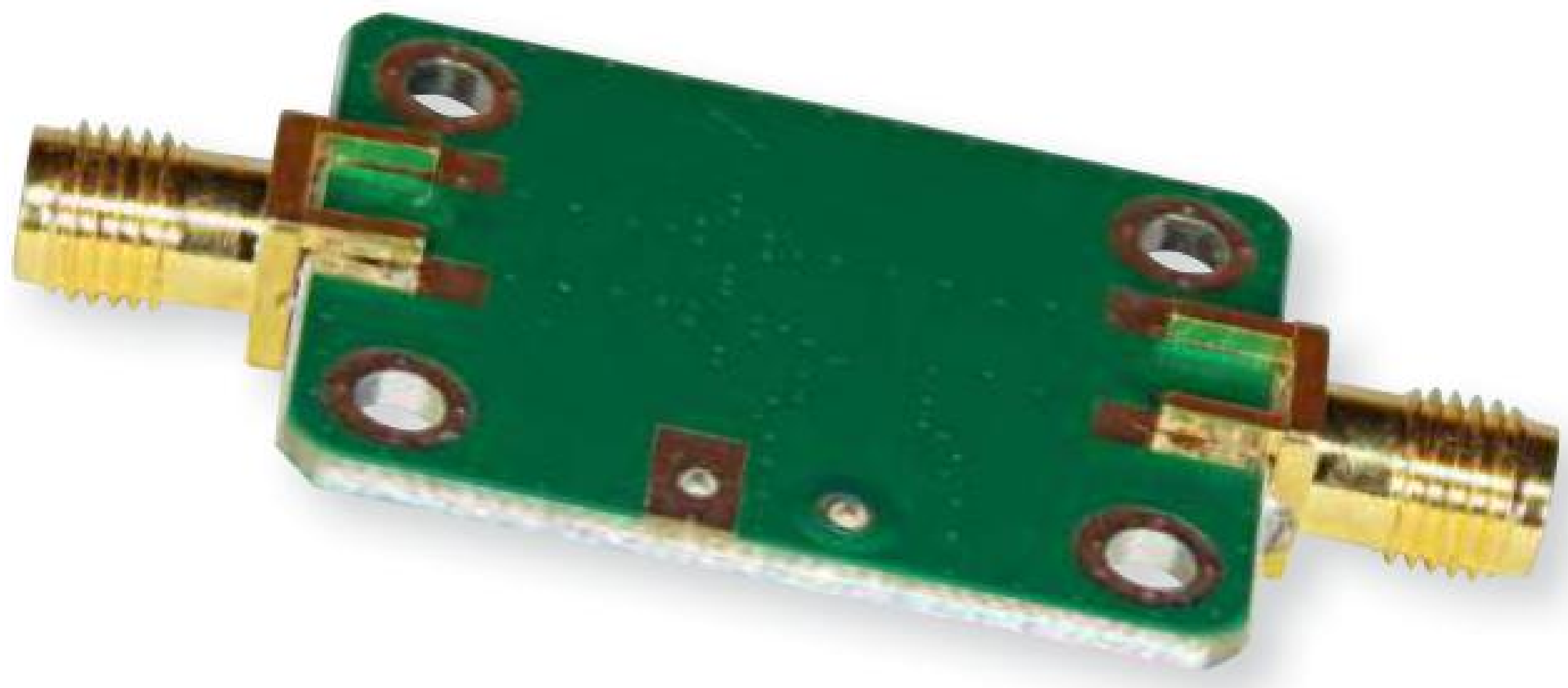
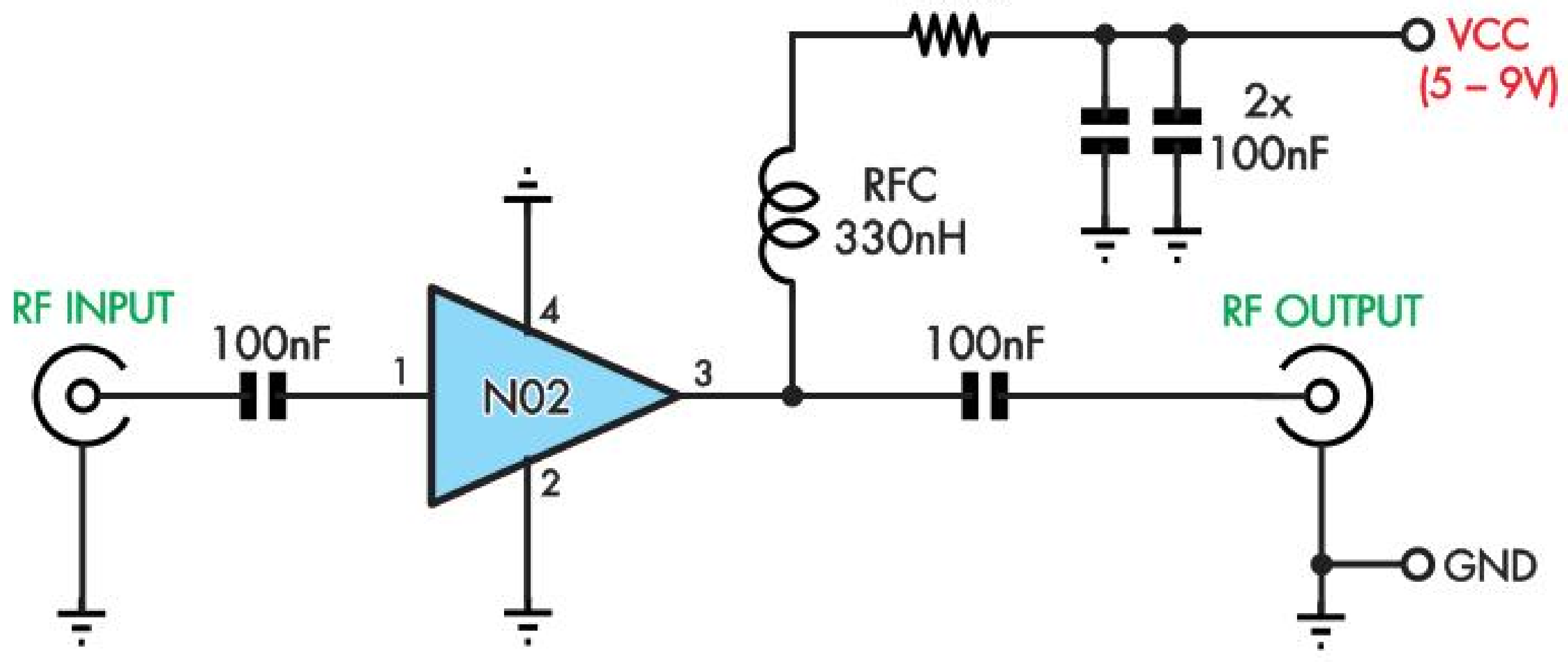


Fig.3: complete circuit for the low-noise wideband amplifier module. It's a simple design incorporating a single IC (N02), which is very similar to an ERA-2SM+, in a 4-pin Micro-X package.



This might be some sort of disabling or gating function for the counter.

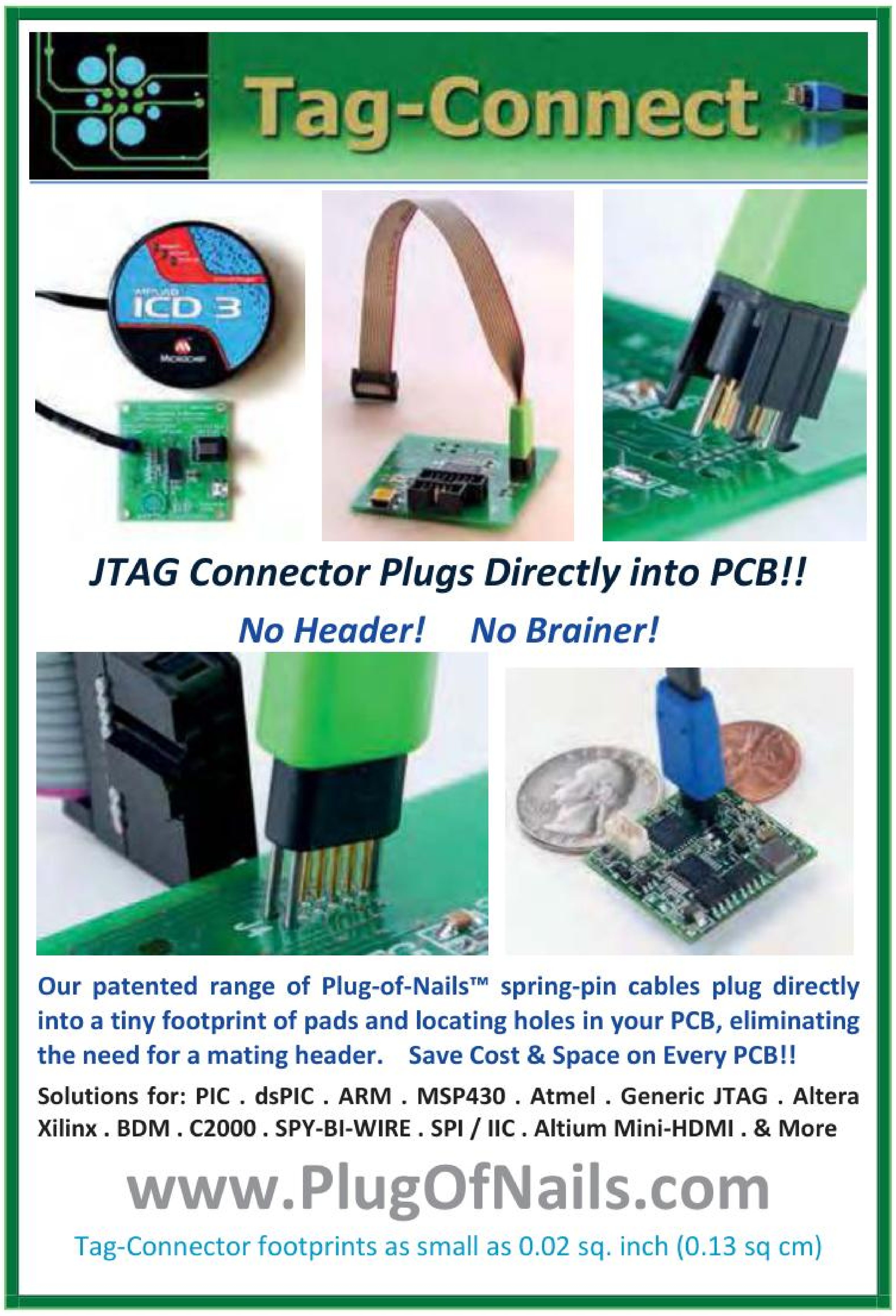
Fitting JP3 causes the value displayed to be about 95.45% of the actual value. Overall, these jumpers may be for a feature that didn't make it into the final product.

Mounting it in a case

Since its performance is quite good, I decided to build it into a UB3 Jiffy box, which is large enough to also house the 9V battery, making it a self-contained portable instrument.

I mounted the module itself behind the box lid/front panel using 9mm-long untapped spacers and 15mm-long M3 screws, replacing the original four very short screws on the top of the module.

I cut a 38 × 18mm rectangular window in the lid for the LCD and mounted a small toggle switch below it for on/off switching. I then drilled a 10mm-diameter hole at the back for access to the module's SMA input connector. A strip of sturdy gaffer tape was also used to hold the battery securely in one end of the box. You could build the module into an even smaller UB5 Jiffy box (83 × 54 × 31mm) if you don't need to include the 9V battery for fully portable operation.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Despite its flimsy on-board on/off switch, the 500MHz frequency counter has the potential to be quite useful for many applications. They're priced at £11.75 from Banggood (**banggood.com** item ID: 1102706). You can also find them on eBay or AliExpress for around £8 or less.

Low-noise preamplifier

Next up is a low-noise amplifier module. Its PCB measures 32.5 × 24.5mm, with SMA input and output connectors at each end and pads for a mini 2-way terminal block for power along one side.

The circuit for the module is shown in Fig.3. The amplification work is done by the 'NO2' IC, which is similar to the Mini-Circuits ERA-2SM+ device used in our recent *UHF Prescaler* (May 2018) and *6GHz Frequency Counter* (October-December 2018) projects.

It's in the same kind of 4-pin Micro-X package and the circuit of Fig.3 is virtually identical to the recommended circuit for the ERA-2SM+.

To check out the module's performance, I connected it to a 9V regulated supply (it draws around 40mA) and linked its RF output to an Agilent V3500A RF power meter.

Then to check its noise performance I terminated its input with 50Ω and measured its output over the module's claimed range of 0.1MHz-2GHz and beyond (up to 4GHz, in fact).

The results of this first test are shown in the blue curve of Fig.4, with the noise level axis on the right. The module's noise level is close to –50dBm across the entire range so it qualifies as a low-noise amplifier or 'LNA'.

For the frequency response, I drove the input with my Gratten GA1484B signal generator, using a short SMA cable and a T-connector at the input with a 50Ω terminator. I ran the signal generator from 0.1kHz to 4GHz with its output level set to –30dBm.

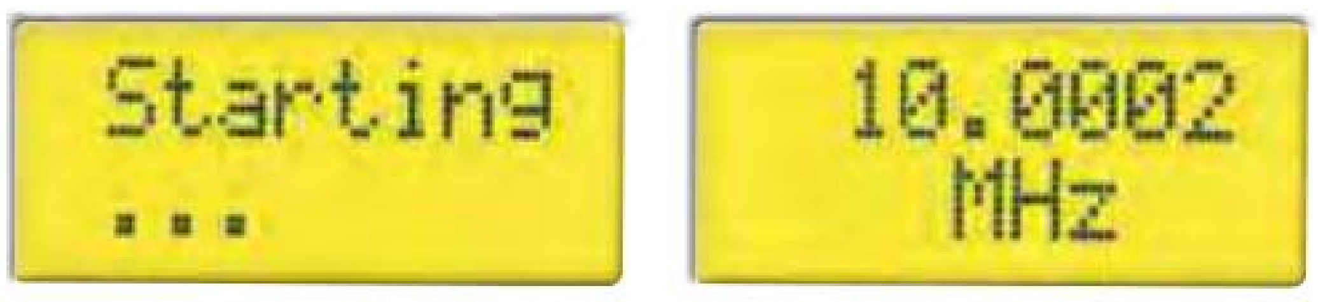
I ran the same test with just the test cable and subtracted the cable loss from the earlier results, giving the red curve in Fig.4, which corresponds to the gain axis.

This shows a gain figure of around 30dB up to 1GHz, dropping to 24dB at 2GHz, then to 16dB at 3GHz and a whisker less than 12dB at 4GHz. So the module provides a useful amount of gain up to 2GHz.

Finally, I did some measurements to see the input signal levels that the module could handle before compression took place.

I actually used a second module for this testing, and the second module turned out to have lower gain than the first, by about 3dB. That's why the levels shown in Fig.5 are all a little lower than in Fig.4.

At just about all frequencies, the maximum input level without compression is close to -20dBm, or 22.4mV across 50Ω. Above this, gain falls away. So it's better to think of it as a low-noise preamplifier rather than a power amplifier.



The 8×2 LCD on the 500MHz frequency counter module will display up to four digits of precision.

They are available from Banggood (**banggood.com** item ID: 1211372) for around £5.70 each, or even less on eBay. You'll pay more for a pair of edge-mount SMA connectors!

Teaming it up with the frequency counter module

Since both modules can be run from 9V DC, you could power them from the same supply, although the combined current draw of nearly 100mA is on the high side for a 9V battery. You would definitely need to use an alkaline 9V battery if you don't want to power them from a plugpack.

It's simply a matter of using a short SMA patch cable to wire the output of the LNA to the input of the frequency counter, and you will have a counter with a sensitivity of around –40dBm from 20MHz to 500MHz, falling to –30dBm at 10MHz, –20dBm at 6MHz and around –10dBm at 3MHz.

This would mean, for example, that you could connect a whip antenna to the LNA input and 'sniff' the transmission from an RF transmitter which operates in the 10-500MHz range by simply bringing the two antennas close together.

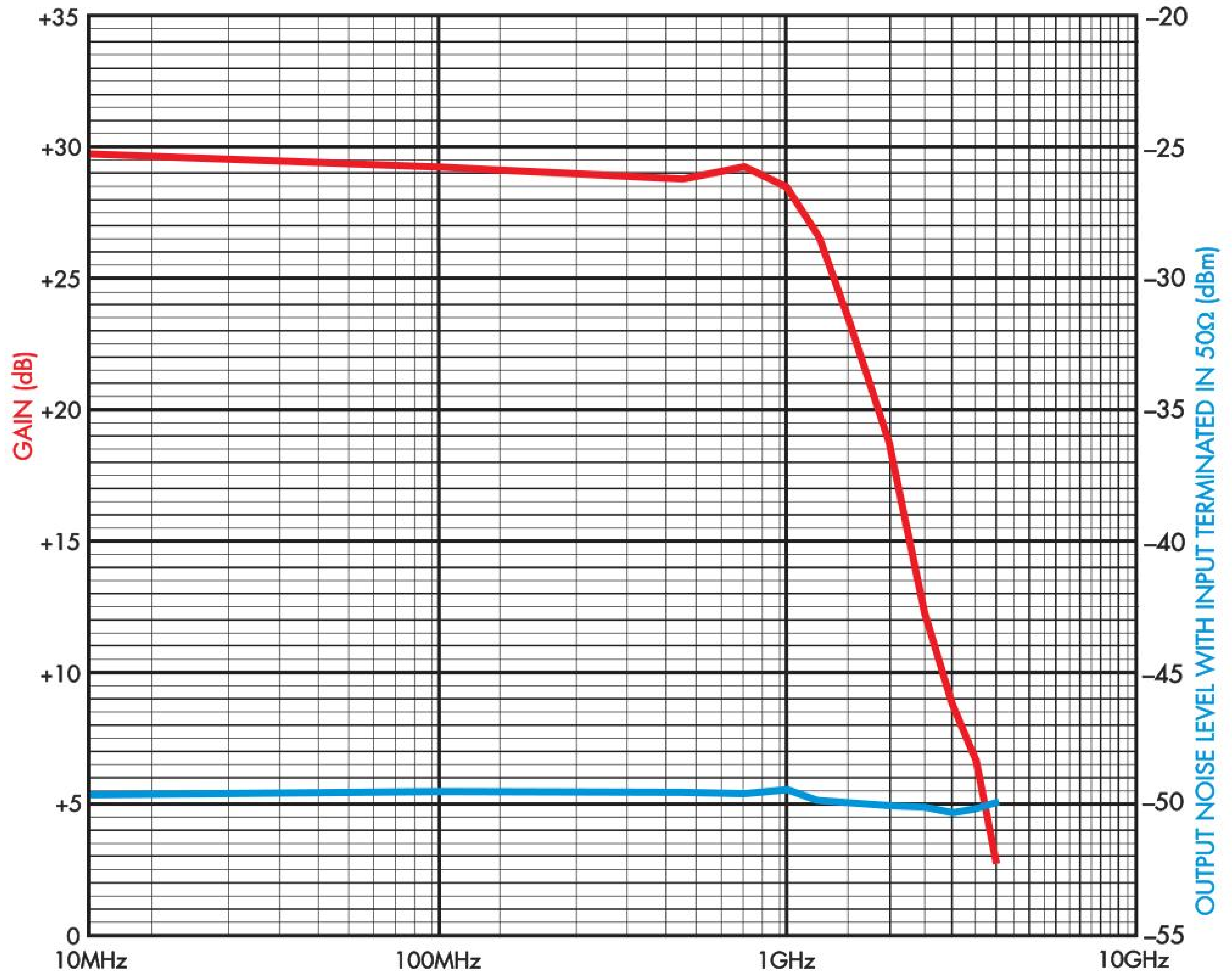


Fig.4: the blue curve represents the noise output of the preamplifier module when terminated with 50Ω, from 10MHz to 4GHz. The red curve shows the gain of the preamplifier over the same range.

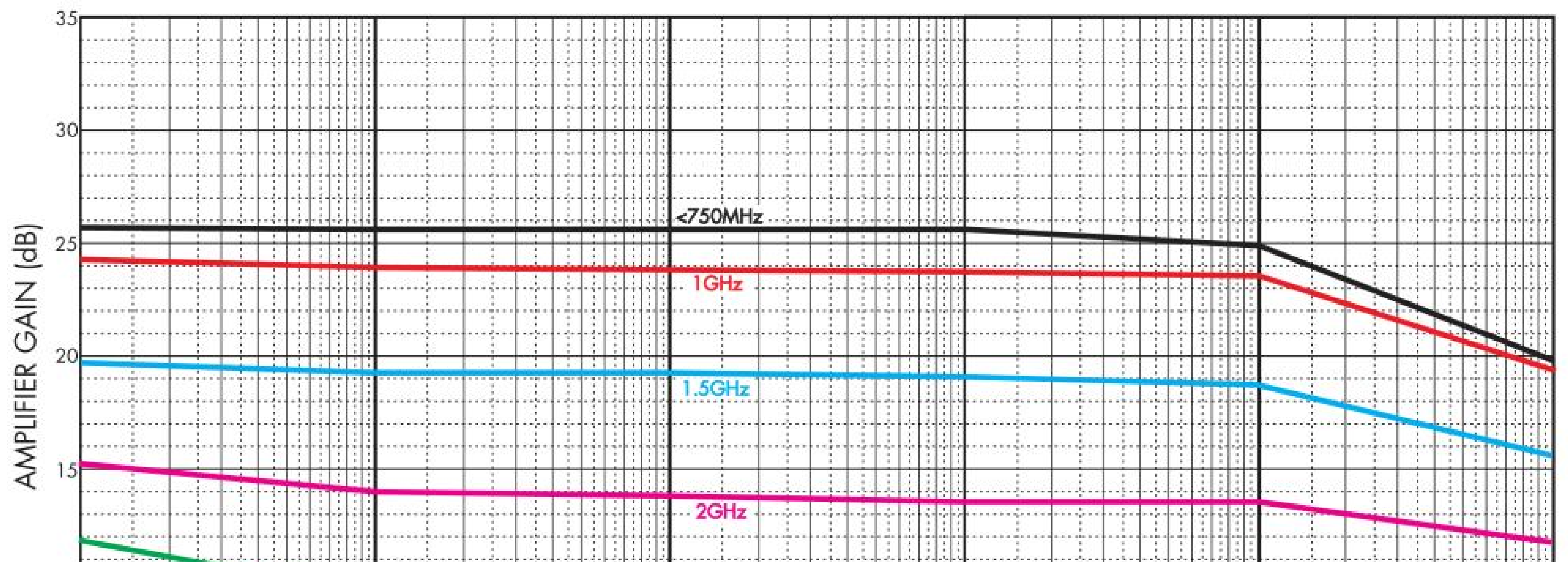


Fig.5: shows the input signal levels the module could handle before compression took place. Note that a second module was used with these tests, one which had a gain about 3dB lower than the module used for the tests in Fig.4.

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MIDI Ultimate Synthesiser

Housing and final set-up

Part 6 | by Paul Cooper | soundtronics.co.uk

In this, the last article of the *MIDI Ultimate Synthesiser* build, the focus is on the final assembly into a bespoke wooden case. Each section of the synth should have been tested to ensure correct functionality prior to assembly, as easy access to the pot side of the main PCB will not be possible after assembly.

Case

A sophisticated project such as the *MIDI Ultimate Synthesiser* would not be complete without being housed in an enclosure. While a ready-built hardwood case is available from Soundtronics, you may prefer the satisfaction of building your own. Fig.84 shows a rendered image of the assembled case, which uses Lamello Cabineo fixings for the corners. With minor alterations, the design could be changed to use wooden dowels in place of the Cabineo fixings.

The case is made up of four wooden parts (two each, cheeks and rails) using 20mm-thick timber plus a 3mm base board which could be acrylic, Dibond, ply or MDF sheet. The left cheek is shown in Fig.85, the right cheek is a mirror image of this. The front and rear rails are identical except for the

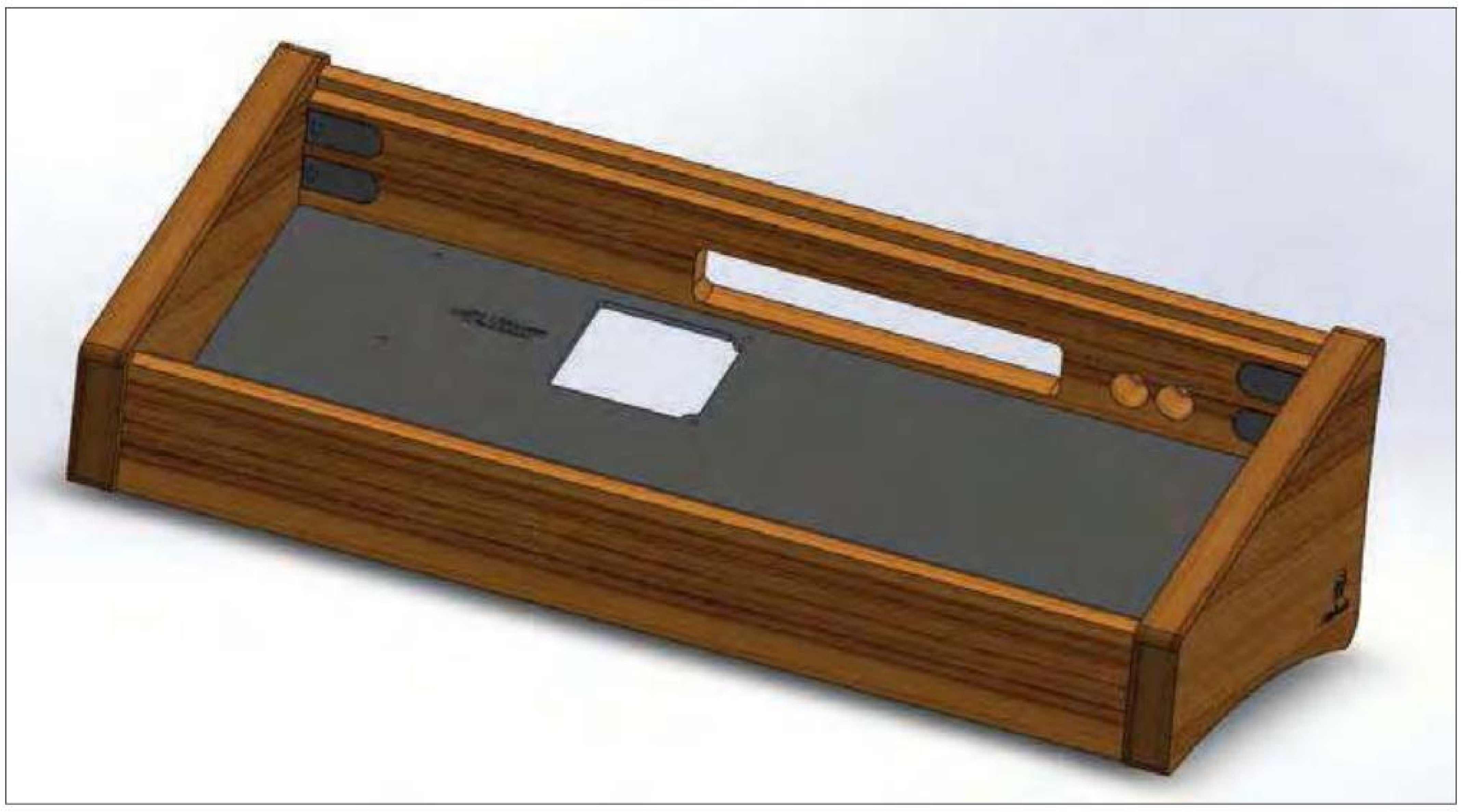


Fig.84. A rendered image of the *MIDI Ultimate* case.

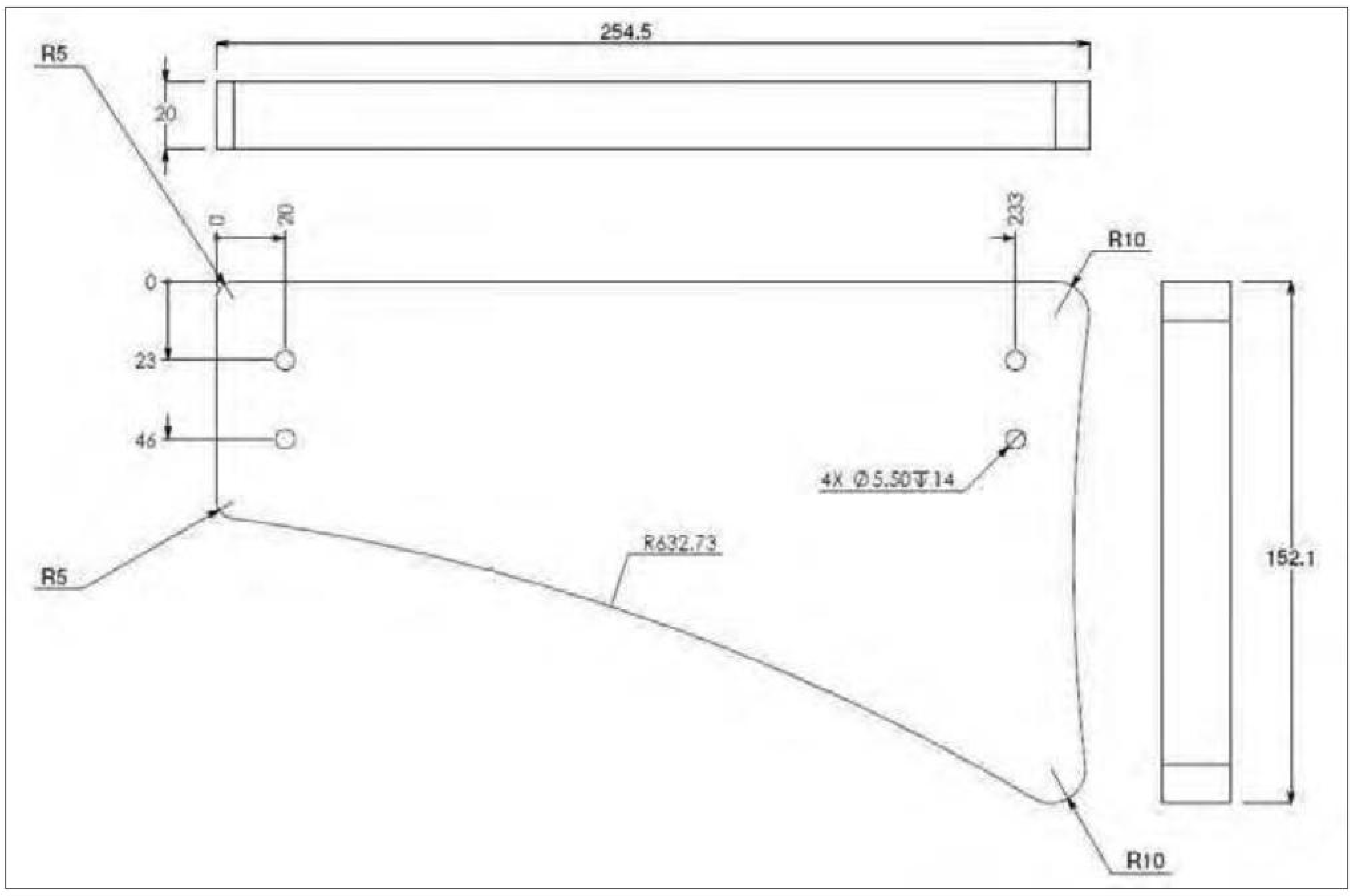


Fig.85. The left cheek is cut from 20mm board, the right cheek is a mirror image.

cut outs in the rear rail. Fig.86 shows the rear rail which has a rebate for the jack socket panel shown in section view A-A.

The wood working tools you have available will influence to what extent you are able to replicate the design. The design uses rebates, so unless you are an experienced handtool-using woodworker, having an electric router is essential for these – but there are workarounds and compromises to the design you could follow to simplify the case build. At Soundtronics, we use a CNC router to cut out rails and cheeks for the various cases we manufacture – see our video at: **https://youtu.be/9X7xyTDbLHI**

The base board (Fig.87) is slid into the 3mm-wide slots in the rails during case assembly.

Rear jack socket panel

First though, We still have one more PCB to build which is for the rear jack sockets (see Fig.88). The rear panel is made from two layers, a 3mm acrylic layer for rigidity and a 1.5mm layer with the socket legends engraving.

Fit the sockets to the panel layers first, ensuring their correct orientation for the PCB, and then solder the PCB to the jacks before finally soldering the 10-way JST lead to the PCB (Fig.89).

The wiring sequence in Fig.89 left to right is black, red, white, yellow, orange, green, blue, violet, grey, brown, and is retained using hot glue. The completed rear panel is inserted into the rebate from the rear (see Fig.90) and retained using four No.4 × 3/8-inch self-tapping screws. These are the same screws that are used for the front panel (12 off) and the MIDI socket PCB (4 off), it is strongly advised to drill a 1.5mm pilot hole for each self-tapping screw first. If not, there is a risk of either splitting the wood or damaging the screw. The self-tapping screws provided in the Soundtronics kit are stainless steel and have a Torx T-10 head, which are more resilient than Pozidriv screws.

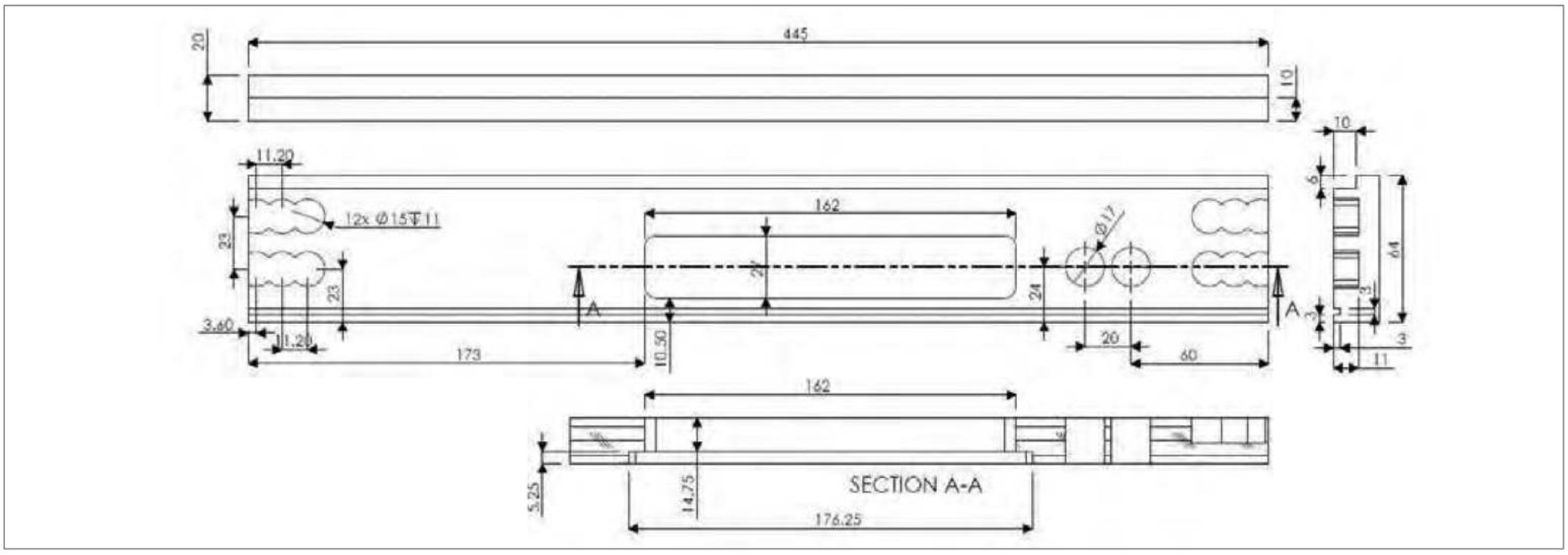


Fig.86. The rear rail is cut from 20mm board; for the front rail simply omit the jack socket aperture and MIDI socket holes.

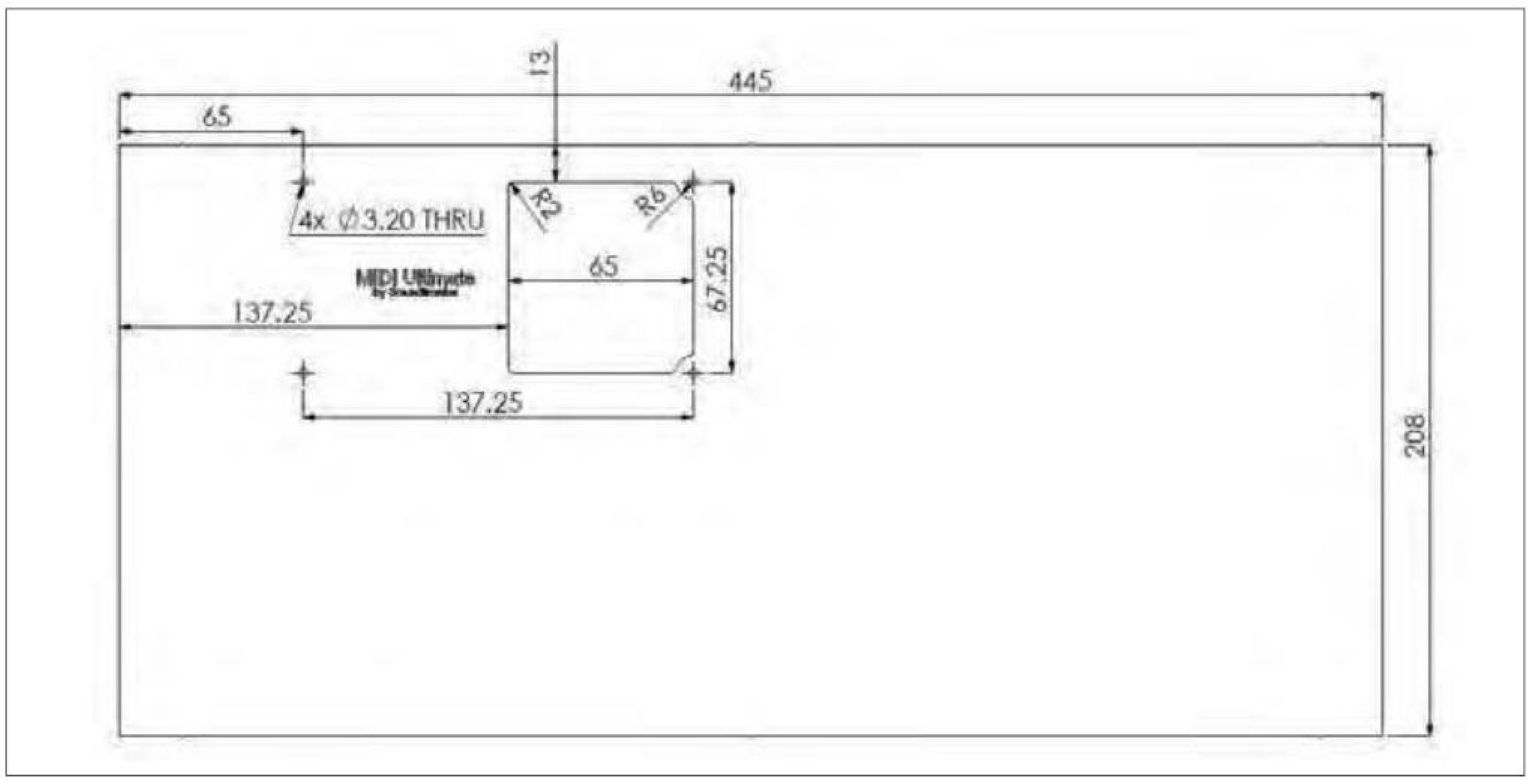


Fig.87. 3mm-thick base board with aperture for the power supply.

Power supply

The power supply case (Fig.91) requires a 6mm hole to be drilled in the side for the mains adaptor AC plug – see Fig.92.

Final assembly

The power supply is fitted to the underside of the base (Fig.93) of the case using four M3 × 12mm screws – do ensure the power socket points to the rear to allow easy insertion of the mains adaptor 12Vac plug. The MIDI

Table 9: Calibration presets

Preset	Function	Issue
P1	White noise level	Part 3, April 2019
P501, P502	VCA	Part 4, May 2019
P901	MIDI Reference voltage	Part 5, June 2019
P101/P102, P201/P202, P301/P302	VCOs	Described below
P401	VCF	Described below

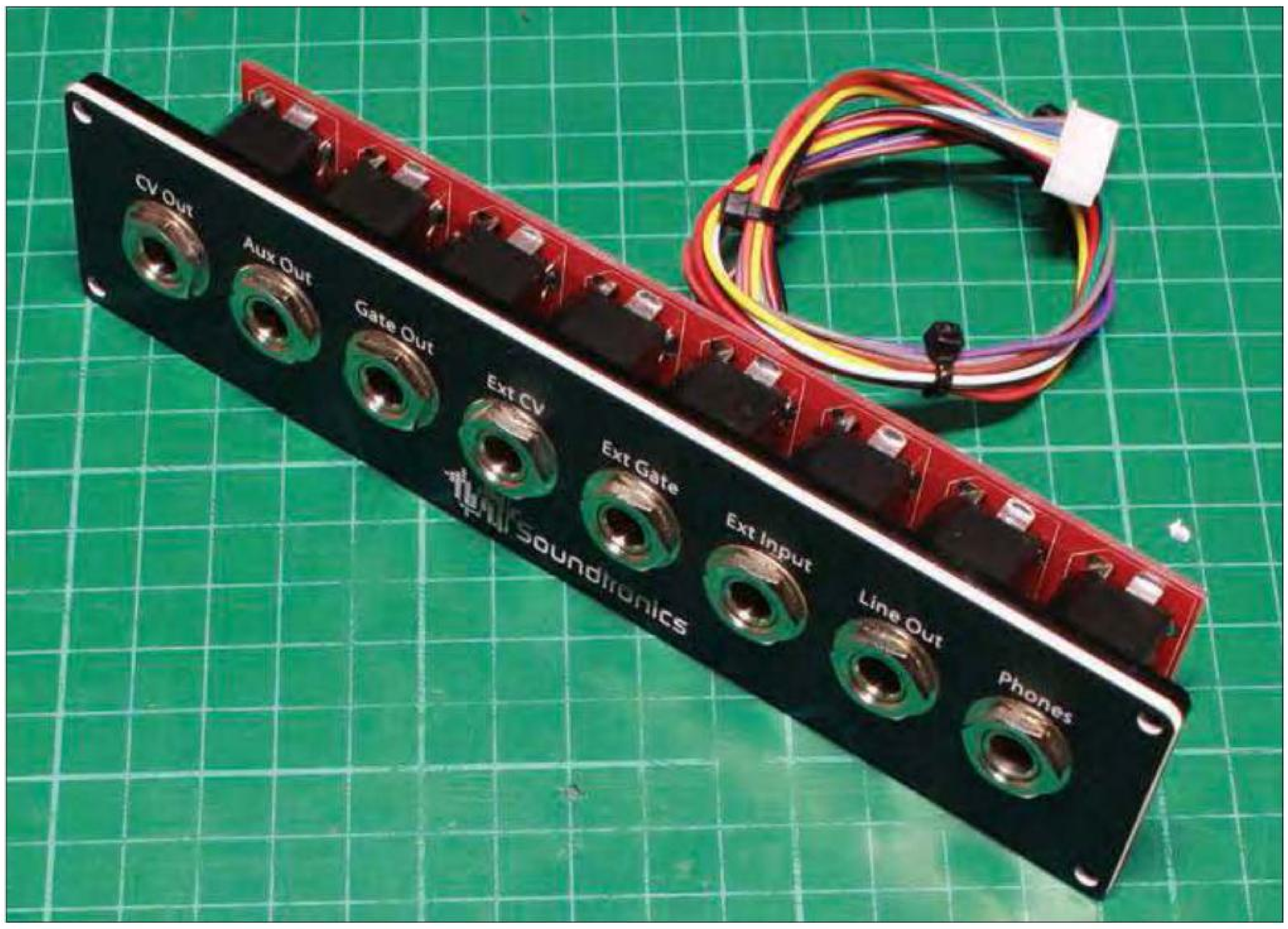


Fig.88. Rear jack socket panel consisting of seven mono sockets and one stereo socket.

socket PCB and jack sockets are fixed using the self-tapping screws described above (remember to drill 1.5mm pilot holes). Access to drill the MIDI socket pilot holes is limited, so use the smallest electric drill you have available.

Front panel assembly

Attaching the main PCB to the front panel can be a bit fiddly, but following this sequence does make the task easier.

1. Using a few drops of CA glue, stick each 10mm-long spacer to the corresponding pad on the PCB. Use an M4 screw to align and weight it down as the glue hardens (Fig.94).
2. Set all 3-position toggle switches to their centre position, 2-way switches to their down position. All switches should have their nuts and washers removed at this point.
3. Place the aluminium back panel over the switches and pots (Fig 95). It may take a little time to achieve this, but it will not require any excessive force. Ensure the back panel is sitting flush on all of the 10mm spacers.
4. Using 15 off M4 × 16mm cap head screws, BZP and fibre washers (Fig.96), screw the PCB to the back panel. Check that the screws do not protrude through the back panel, they should all finish just below the surface.
5. Now place the front panel over the switches and pots in a similar manner to the back panel. Ensure the front panel sits flat on the back panel before all of the switch lock nuts are fixed. Do not use pliers to tighten up the lock nuts as the risk of damaging the front panel is too great. Hollow shaft nut spinners or long reach sockets are best, but even then ensure the face of the socket is smooth with no sharp edges or burrs from chromium plating. For the toggle switches use an M8 socket, push buttons are M10 and the MIDI channel switch is M14 (Fig.97).
6. The MIDI switch (Fig.98) is rather delicate, so depending on the knob style chosen, it is best to cut the shaft to length prior to fitting to the panel. Hold the end of the shaft in a vice and using a junior hacksaw, cut the shaft to the desired length. Do not apply excessive force to the knob when fitting the shaft, as it is all too easy to burst open the rear casing of the switch – yes, I did do that when evaluating different knob options!
7. Next, place the panel into the case, mark each of the 12 fixing holes, remove the panel and drill the 1.5mm pilot holes. Before inserting the screws, we have some final calibration to carry out

VCO / VCF calibration

There are 11 multi-turn presets (Table.9) used in the calibration of the synth, some of which have already been covered in previous parts of this series.

The VCOs and the VCF calibrations are to ensure their voltage/frequency relation follows the 1V/octave. Traditionally, you would use an accurate voltage source that can be stepped in 1V increments, or the more time-consuming route of a variable voltage source and an accurate voltmeter. However, we can make use of the MIDI interface and a MIDI keyboard to generate the 1V increments. Additionally, a frequency meter is required for which many hand held digital multimeters have this function, or we can use the sound card scope described in *Part 2* (*EPE*, March 2019). Another option is to use a digital guitar tuner with a

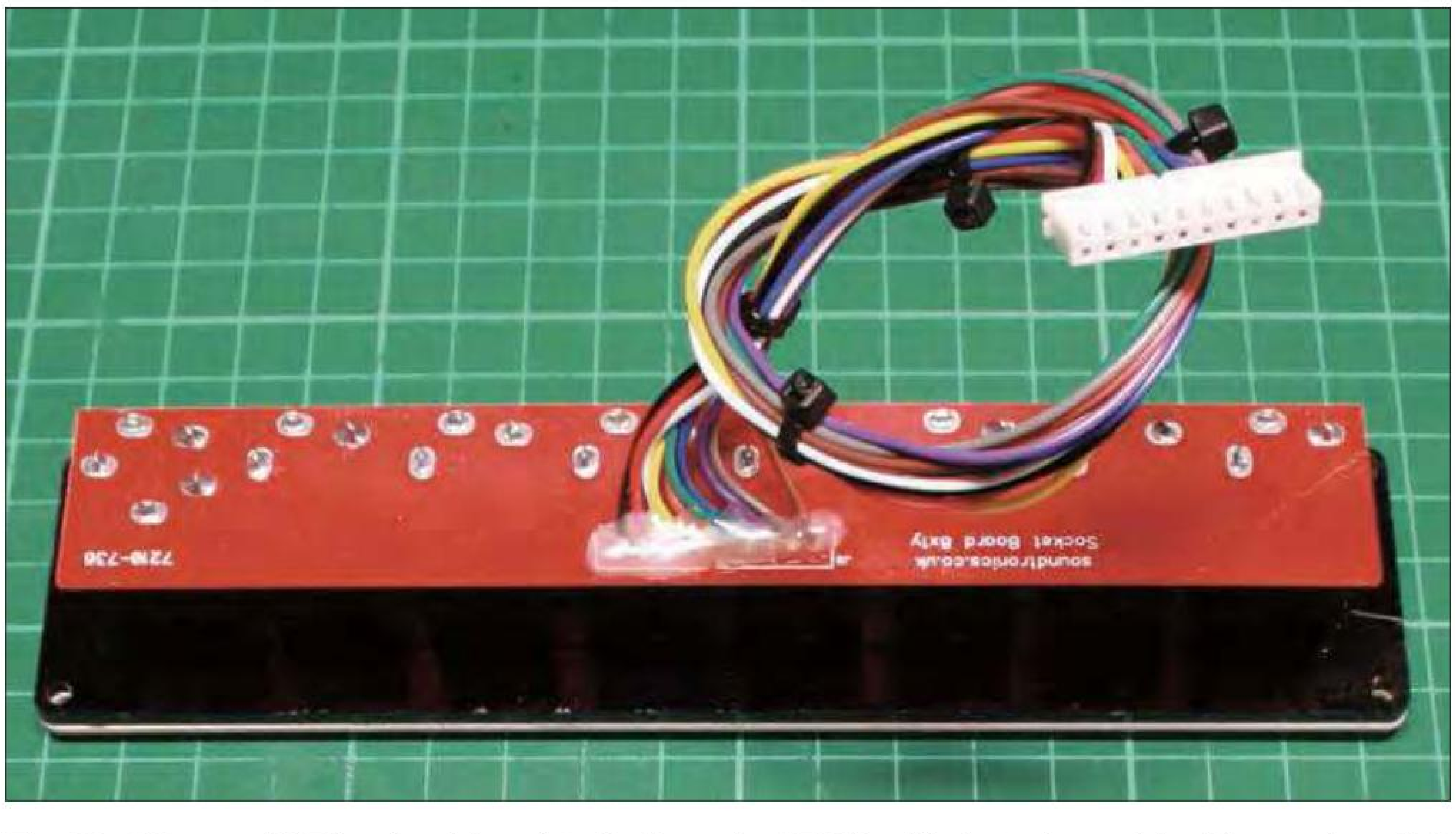


Fig.89. 10-way JST lead soldered to jack socket PCB with hot glue added for strain relief.

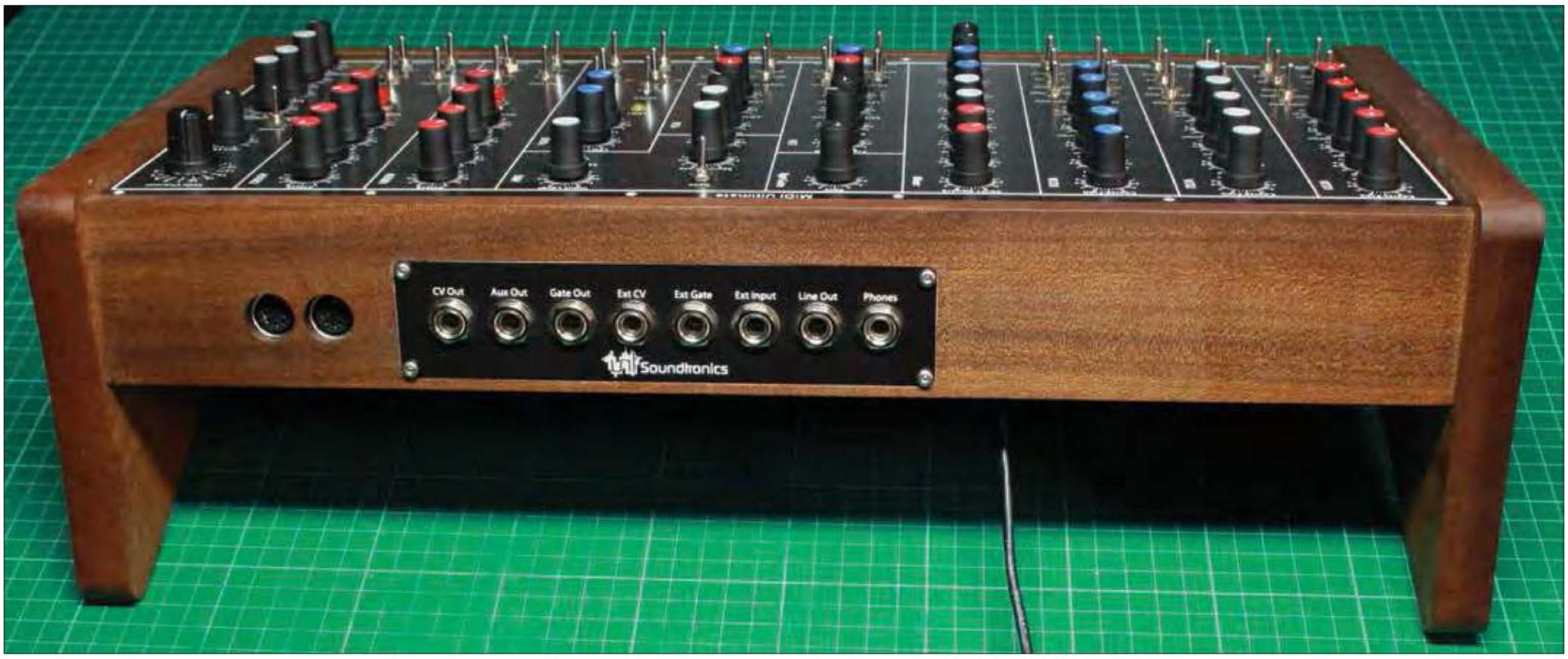


Fig.90. Rear view of the first prototype *MIDI Ultimate* with the recessed jack socket panel.

jack input, which can be picked up for under £20.

Before commencing calibration, power the synth up and leave to stabilise to room temperature for 30 minutes. The following calibration procedure describes VCO1, repeat the procedure for the other two VCOs, remembering to only have the respective square control on the mixer turned to maximum at any one time.

For each VCO, set the VCO fine frequency control to 5, all switches to mid-position except for the 'MIDI CV' switch, pulse width to 50%, modulation pots to 0. All mixer controls to 0. For the VCF, all pots to 0, all switches to centre except for 'MIDI CV'. MIDI channel switch to 1.

Connect the MIDI keyboard to the MIDI input socket of the synth with its MIDI channel set to 1. Connect the frequency meter to the mixer output, as shown in Fig 41 of *Part 2* of the series. It is also useful to connect the CV output socket to a digital voltmeter.

Power up the synth and press the lowest 'C' key. If it does not give 0V, transpose the keyboard until it does. Set VCO1 Square mixer pot to 10. Now do the following:

1. Press bottom 'C' so the CV is 0V.
2. Using the coarse and fine frequency controls, set the frequency to 100Hz.
3. Press the 'C' key 3 octaves higher (use the transpose button if you only have a 2 octave keyboard), the voltage will read 3V, the frequency should be 800Hz.
4. If the frequency is higher than 800Hz, adjust the '1V/oct' preset so that the frequency is made even higher. This sounds counter-intuitive and not typical of a zero/span calibration. For example, if the frequency was 840Hz, increase to 855Hz. If the frequency is lower than 800Hz, then lower the frequency even more. For example, if the frequency was 790Hz, adjust the same preset to 788Hz.
5. Go to step 1 until you have 800Hz at step 4.
6. Press the 'C' key two more octaves higher, the CV will be 5V.
7. Adjust the 'HF Freq Trim' preset until the frequency is 3.2kHz.
8. Go to step 1 until you achieve 3.2kHz at step 7.

The above is not a precise science, but it is possible to achieve good tracking to within a few hertz between 100 and 800Hz and 10-15Hz up to 3.2kHz, if not better.

Repeat the calibration for VCO 2 and VCO 3 but set the coarse frequency control on VCO 1 to minimum first – see the 'Crosstalk' section below.

The VCF calibration is more straightforward. Ensure all mixer controls are set to 0. Connect the frequency meter to the VCF output as shown in

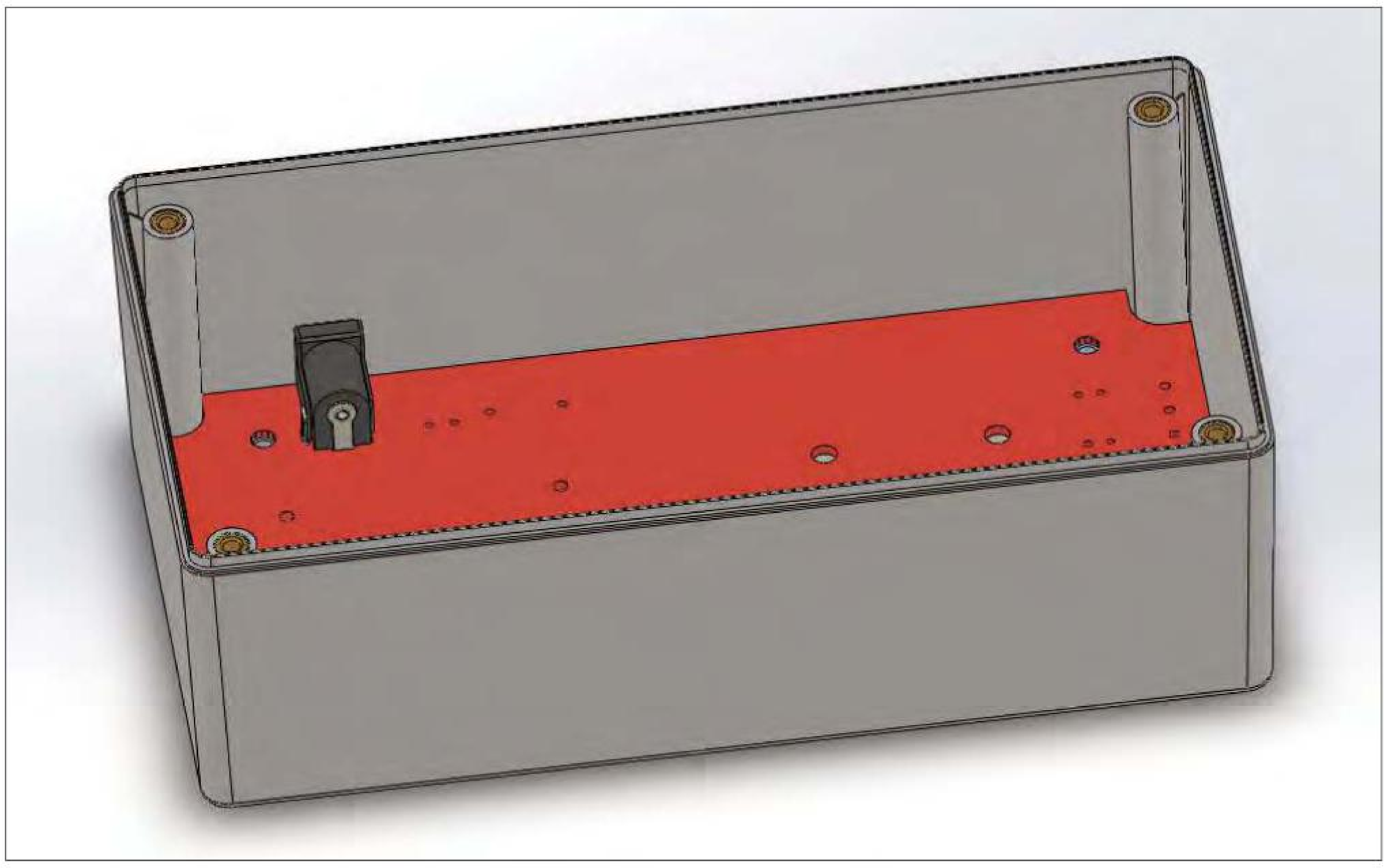


Fig.91. Rear view of power supply case.

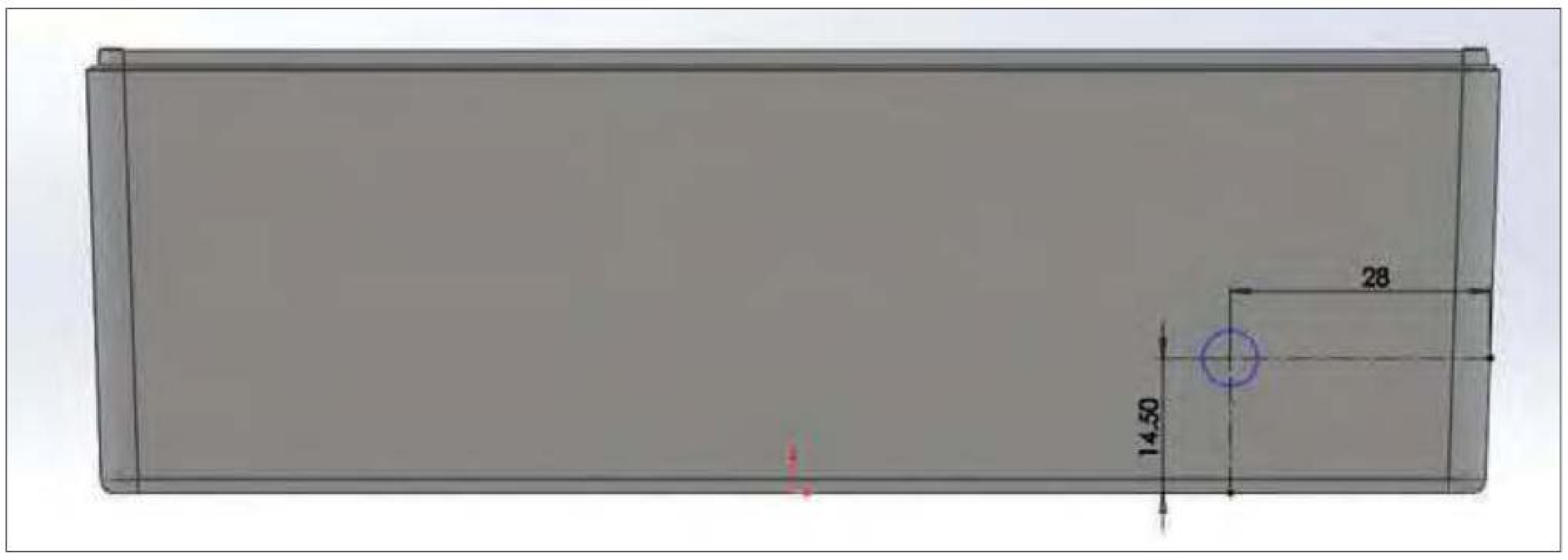


Fig.92. Front view of power supply case with 6mm hole for the DC power plug.

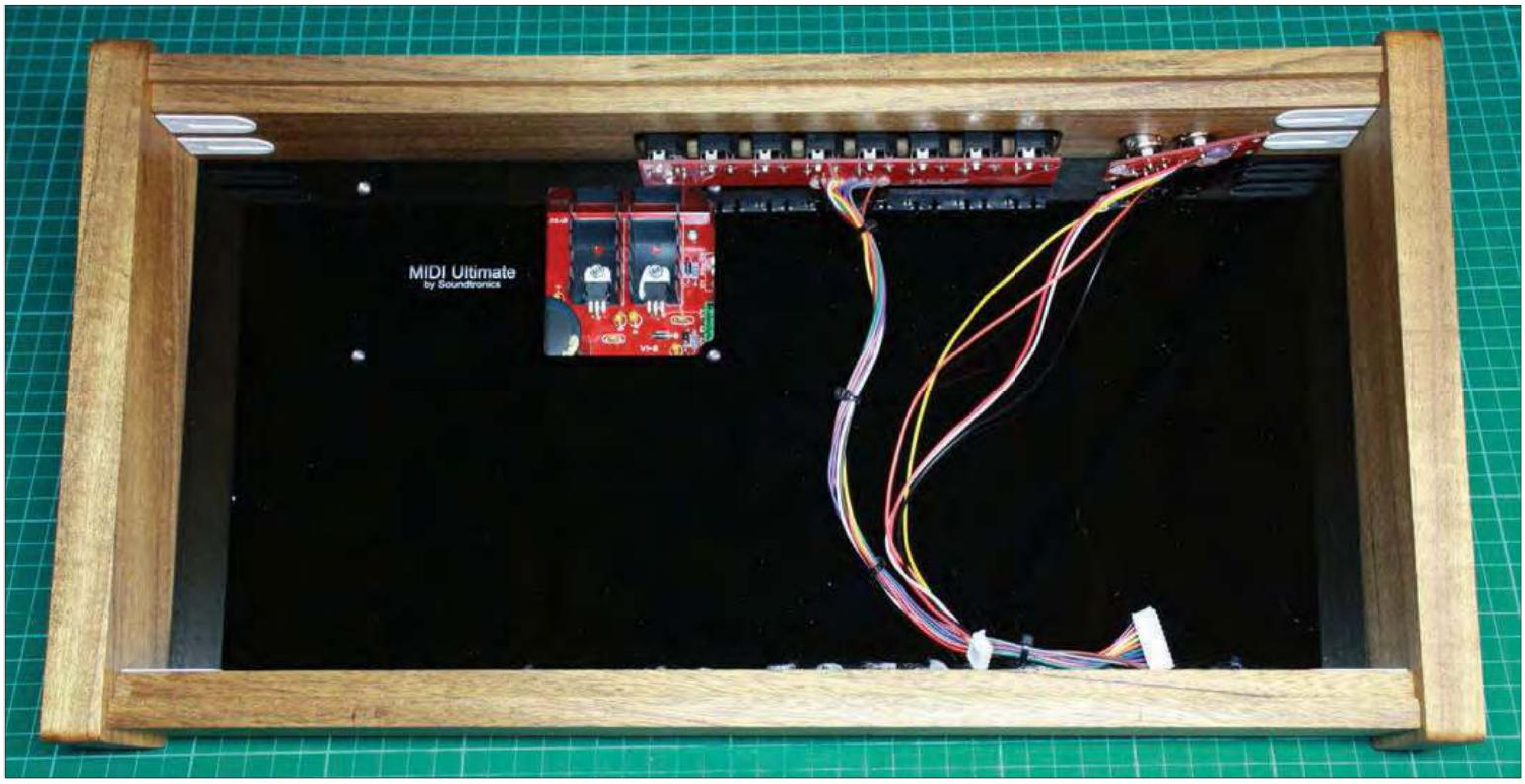


Fig.93. The power supply and jack sockets fitted; the MIDI sockets PCB ready for attaching to the case.

Fig 40, also in *Part 2* of the series. Increase the resonance control to 10 so that the VCF self-oscillates. Now do the following:

1. Press bottom ‘C’ so the CV is 0V.
2. Using the cut-off frequency control, set the frequency to 200Hz.
3. Press the ‘C’ key two octaves higher, the CV voltage will read 2V, the frequency should be 800Hz.
4. If the frequency is higher than 800Hz, adjust the ‘Scale Trim’ preset so that the frequency is made even higher in a similar way to that of the VCOs. If the frequency is lower than 800Hz, then lower the frequency even more.
5. Go to step 1 until you get the 200 to 800Hz tracking.

This concludes the calibration and you can now finally fit the front panel to the case after first ensuring the two JST and single power plugs are inserted.

Getting started making sounds

If you are new to analogue synthesis, the number of switches and knob controls may appear a bit daunting at first, but you will soon become familiar with these controls through experimentation. Don’t be surprised if your settings result in no sound output while you become accustomed with all the synth features. Fig 5 in *Part 1* (*EPE*, February 2019) is a useful resource to refer to during this learning process. One approach is to start off with a basic idea of a sound and try and create it. Then start trying other settings and before long, you will have created something unexpected – some of your best sounds are likely to come about by accident.

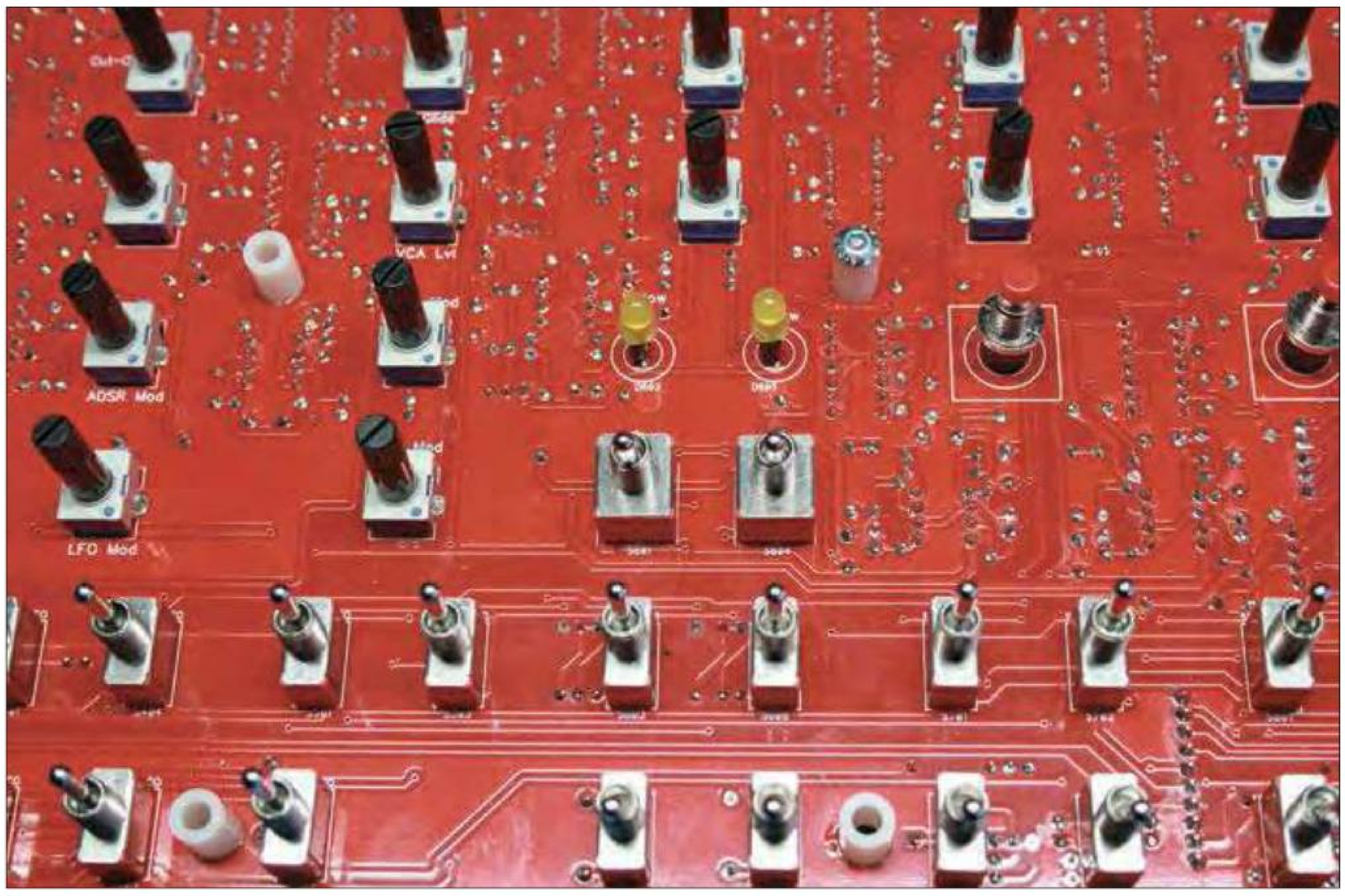


Fig.94 Use CA glue to stick each of the 15 spacers to the PCB pads; use an M4 screw to keep the spacers in position while the glue hardens.

Further reading

There are a number of books available covering analogue synthesisers, but most focus on their history and the musicians who use them rather than how to actually make music with them. *Analog Synthesizers – understanding, performing, buying* (Published by ‘Focal Press’) by Mark Jenkins is an excellent read in this regard. In *Part 1* (*EPE*, February 2019), credit was given to the late Ray Wilson of Music From Outer Space, whose designs formed the basis of the *MIDI Ultimate*. He wrote a book called *Analog Synthesizers* (Published by ‘Make:’). This book is available from Amazon for under £13, and while it covers the building of the ‘Noise Toaster’, there is plenty of other content covering analogue synthesis in general. For a final recommended read, see *Welsh’s Synthesizer Cookbook* by Fred Welsh. Not so readily available in the UK, but it can be imported from the US. This book differs in that it covers each section of an analogue synth in detail, reverse engineering existing sounds through harmonic analysis so as to recreate them on your own synth. It has patches you can follow to emulate traditional musical instruments as well as other pure synth sounds.

A PDF of an A3-size blank patch sheet (Fig.102) is available at **soundtronics.co.uk** and on the *PE*

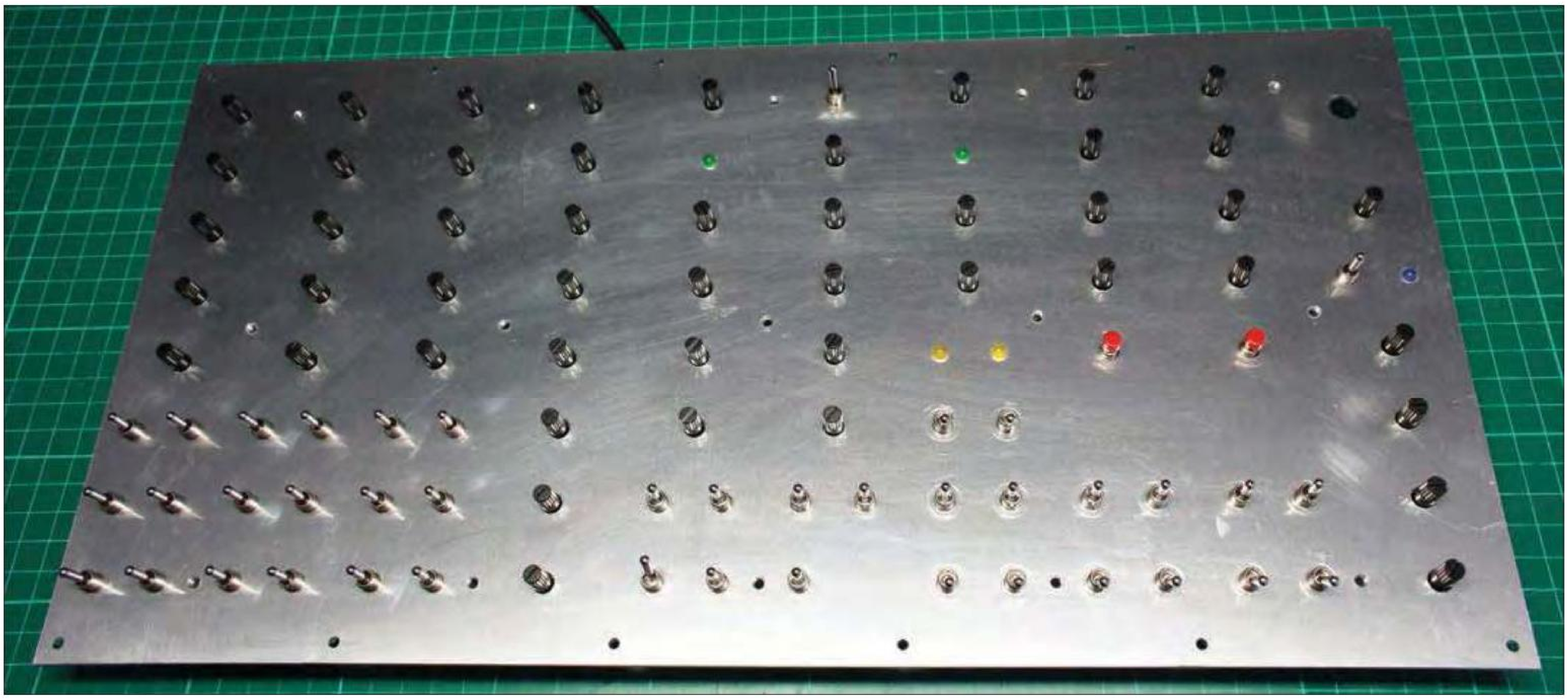


Fig.95. The aluminium back panel placed over the switches and pots prior to the front panel being applied.

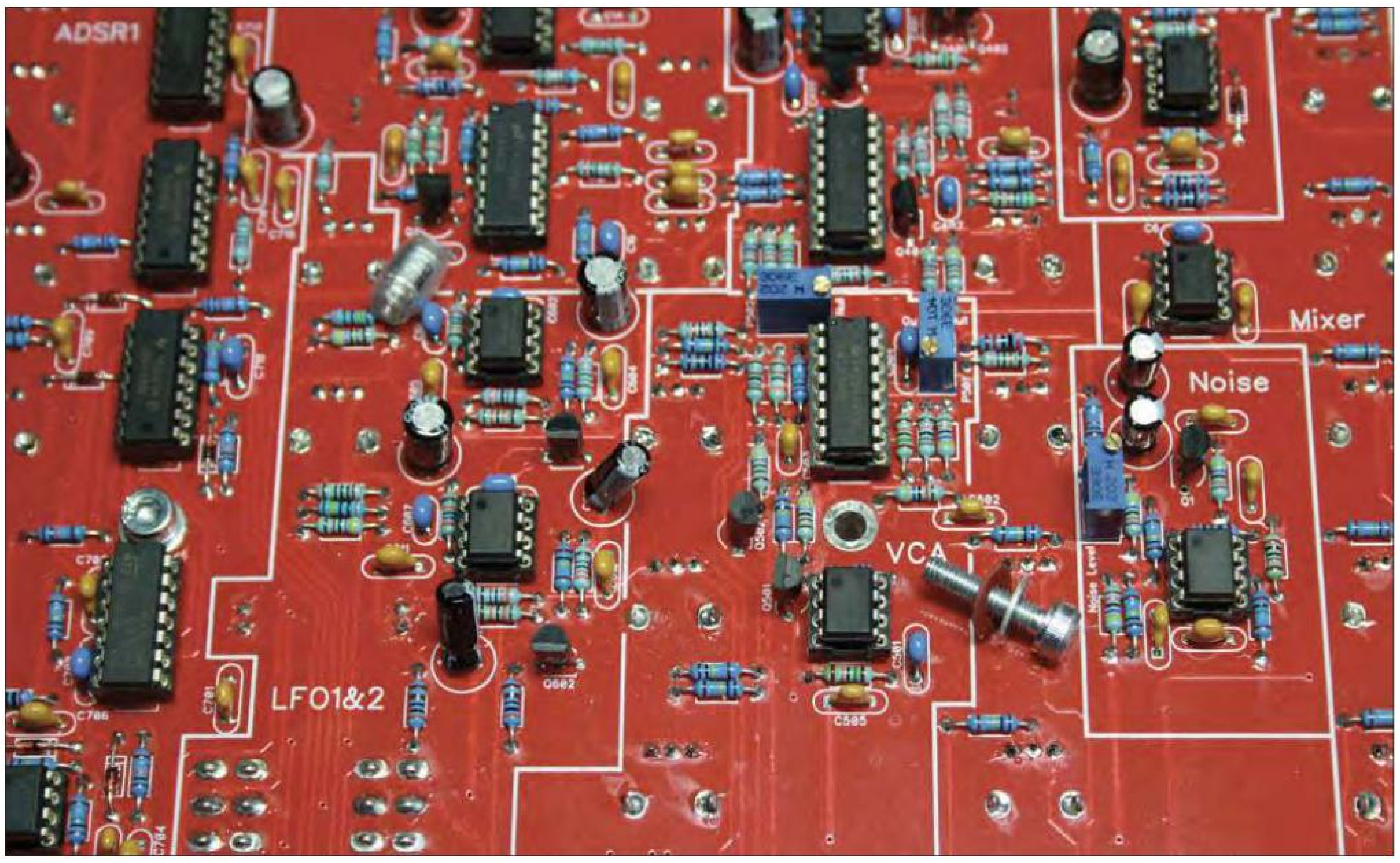

ADSR1
Mixer
Noise
VCA
LFO1&2

Fig.96. The PCB is fixed to the back panel using 15 M4 × 16mm cap head screws with a BZP and fibre washer to ensure the screw does not protrude beyond the back panel.

website where you can note your settings of each of the controls so you can recreate that fantastic sound you just created again in the future. You can print the patch sheet out on A4 landscape if you do not have access to an A3 printer; you just need a finer pen to mark the positions of the knobs. Along with the blank patch sheet are some pre-prepared ones (Fig.99) that you can try out and further adapt the sounds. Being analogue in nature, the settings are not absolute and may require some fine tuning to fully recreate the intended sound.

Crosstalk

Chris T on the *MIDI Ultimate* support blog on the Soundtronics website reported hearing VCO 1 on the mixer output even when its mixer pots were

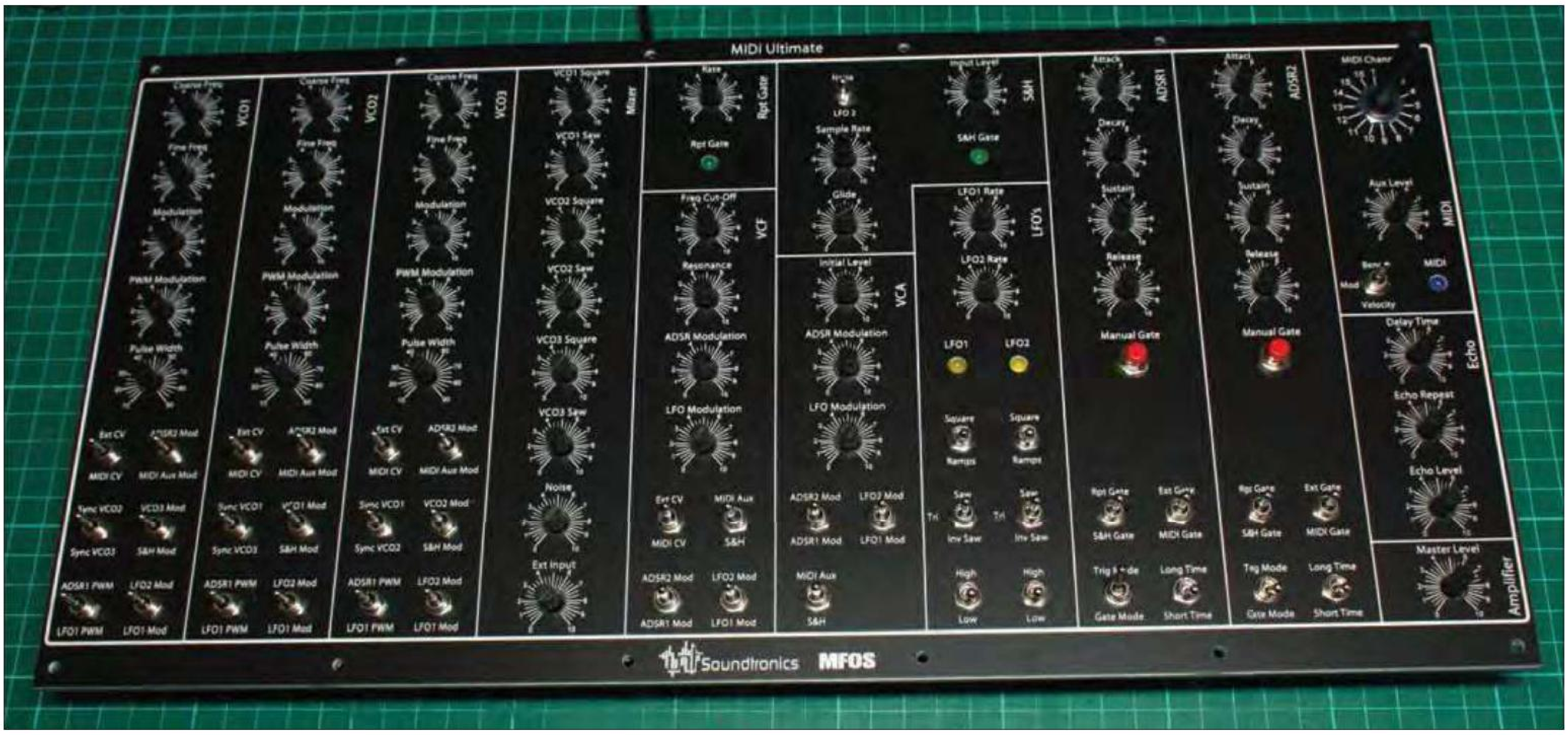
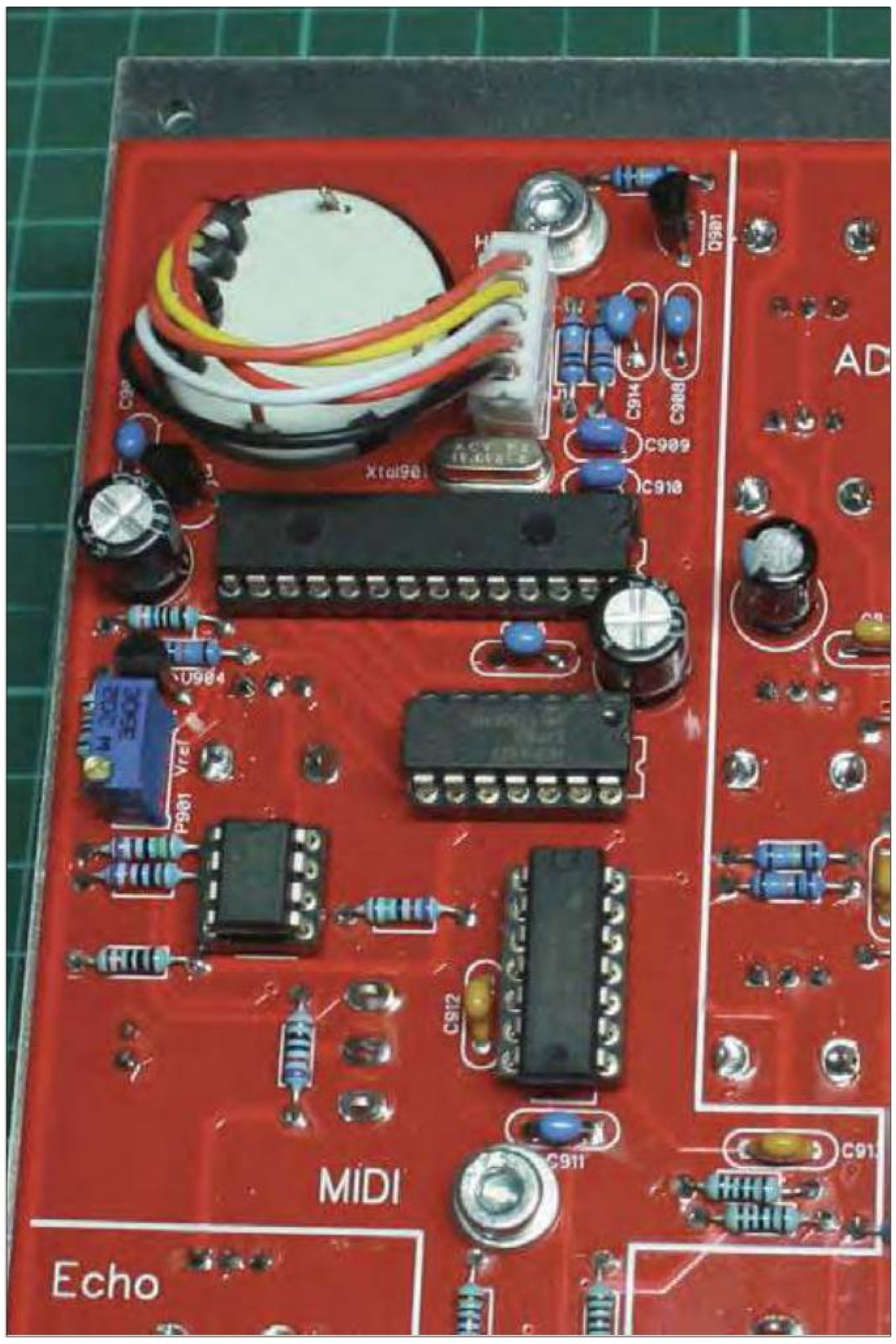
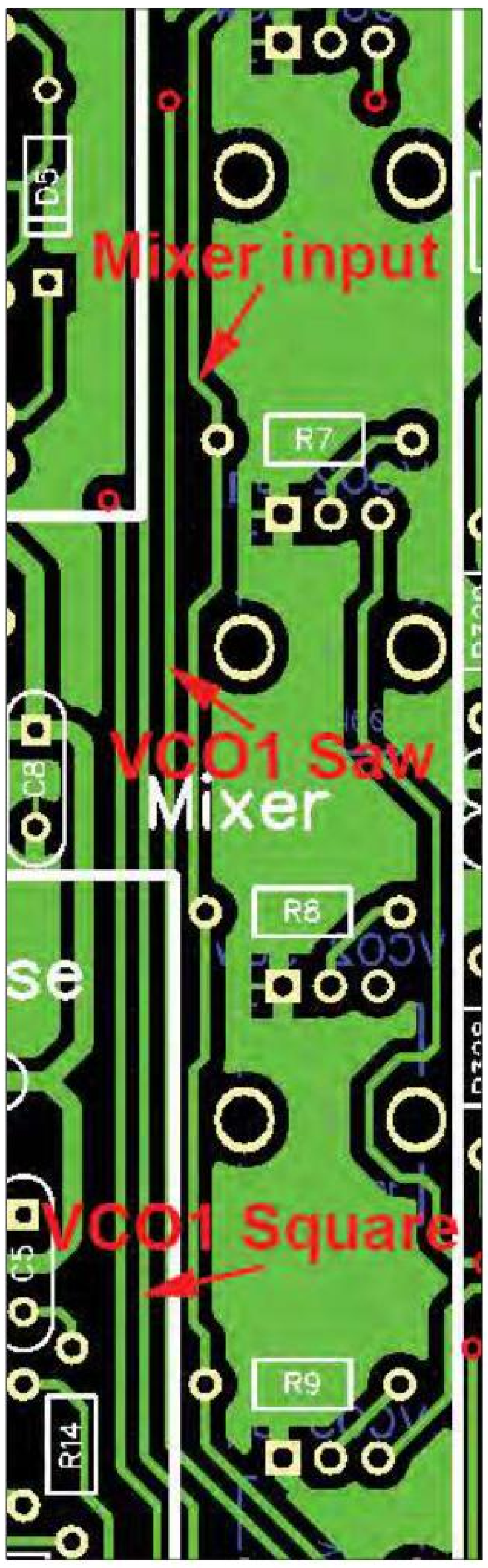

MIDI Ultimate
VCO1
VCO2
VCO3
Mixer
Rpt Gate
VCF
VCA
S&H
LFO's
ADSR1
ADSR2
MIDI
Echo
Amplifier
Soundtronics
MFOS

Fig.97. Front panel attached and all lock nuts fixed in place.


AD
MIDI
Echo


Mixer input
R7
VCO1 Saw
Mixer
R8
VCO1 Square
R9

(Left) Fig.98. MIDI switch and JST connector. (Right) Fig.100. Crosstalk due to close proximity of VCO1 square and sawtooth traces to the mixer input.

set to 0. We have investigated this and discovered it is due to crosstalk between three parallel PCB traces (tracks), one trace is the input to the mixer the other two are the VCO 1 square and sawtooth signal traces (Fig.100). The fast rise and fall times of the waveforms are being seen as narrow spikes on the mixer input. Fortunately, the low-pass VCF attenuates these 20μs spikes so they are not audible on the output. The PCB layout is relatively dense due to the numerous patching traces between the synth sections, so avoiding crosstalk is challenging. A rule of thumb is to have a gap between clock (which is what the VCO outputs are effectively classed as) and signal traces that is three times the trace width, or to put a ground plane in between traces.

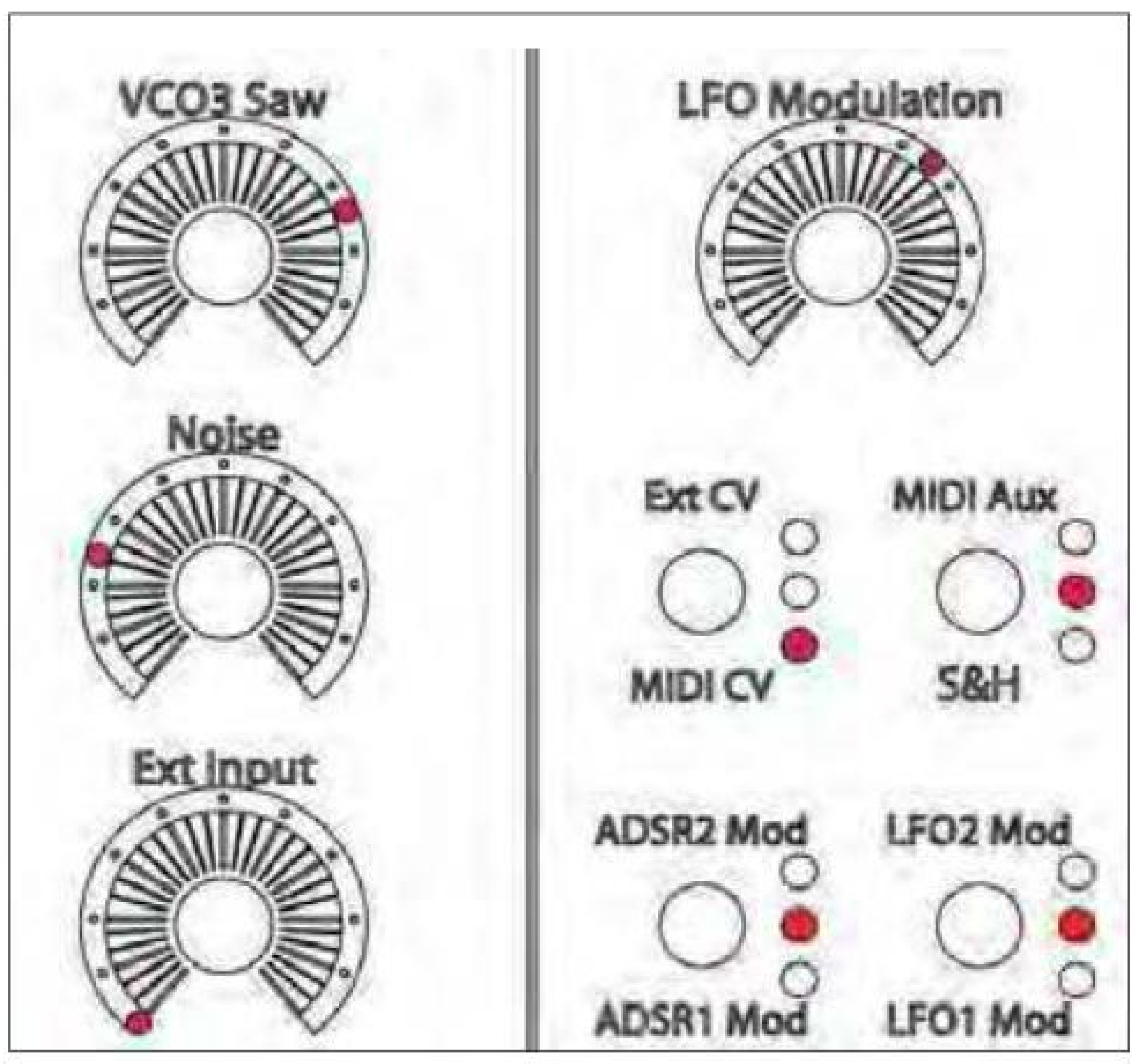

VCO3 Saw
LFO Modulation
Noise
Ext CV
MIDI Aux
MIDI CV
S&H
Ext Input
ADSR2 Mod
LFO2 Mod
ADSR1 Mod
LFO1 Mod

Fig.99. Extract from a patch sheet, the blank full version is shown opposite.

Hacks

With the detailed constructional information provided in this series of articles, those with a good understanding of electronics may wish to customise the *MIDI Ultimate* to better suit their own application. Areas that are open to modification include:

Linear CV

Our focus has been on the 1V/octave frequency relationship, but there are times when a linear relationship is preferred for modulation, especially at audio frequencies (FM synthesis). Each VCO has a linear CV point

MIDI Ultimate

Fig.101. The *MIDI Ultimate* in a 5U modular synth.

identified on the schematic that could be routed to additional jack sockets.

Additional VCF inputs
The VCF input is connected to the mixer output, but an external input to the VCF could be added by replicating C406 and R417. The VCA can be modified in a similar way.

Additional CV inputs
With the use of voltage summers on the CV circuits to the VCOs, VCF and VCA, it is straight forward to add dedicated external CV inputs to any of these sections.

Component values
Many component values can be changed to alter the operating range. Whether this is the frequency range of an oscillator, cut-off frequency range of the VCF or the timing values of the ADSRs, all are open to experimentation.

Where next?

I hope the *MIDI Ultimate* series has inspired you to build your own analogue synth and then look at expanding you synthesiser horizons. The *MIDI Ultimate* has been designed with this in mind and can be integrated into a 5U modular synth system (Fig.101).

This allows for additional modulation, filter types and signal processing modules such as ring modulators and phase shifters to further extend the range of sound possibilities. We do have plans for further projects in *PE* – perhaps a self-contained expander for the *MIDI Ultimate* featuring additional processing modules – watch this space and let us know what you'd like to see next!

MIDI Ultimate
download package

The *MIDI Ultimate Synthesiser* series of six articles was published from February to July 2019.

It included large circuit diagrams that used small text to enable the diagrams to fit across a page. To help readers who may have found some of the text just a little too small to read easily, all the diagrams are available in zoomable PDF format for download from the July 2019 issue's page on the *PE* website. The download package also includes:

- *MIDI Ultimate* block diagram
- Blank patch sheet
- MIDI code
- Full parts list with sourcing advice.

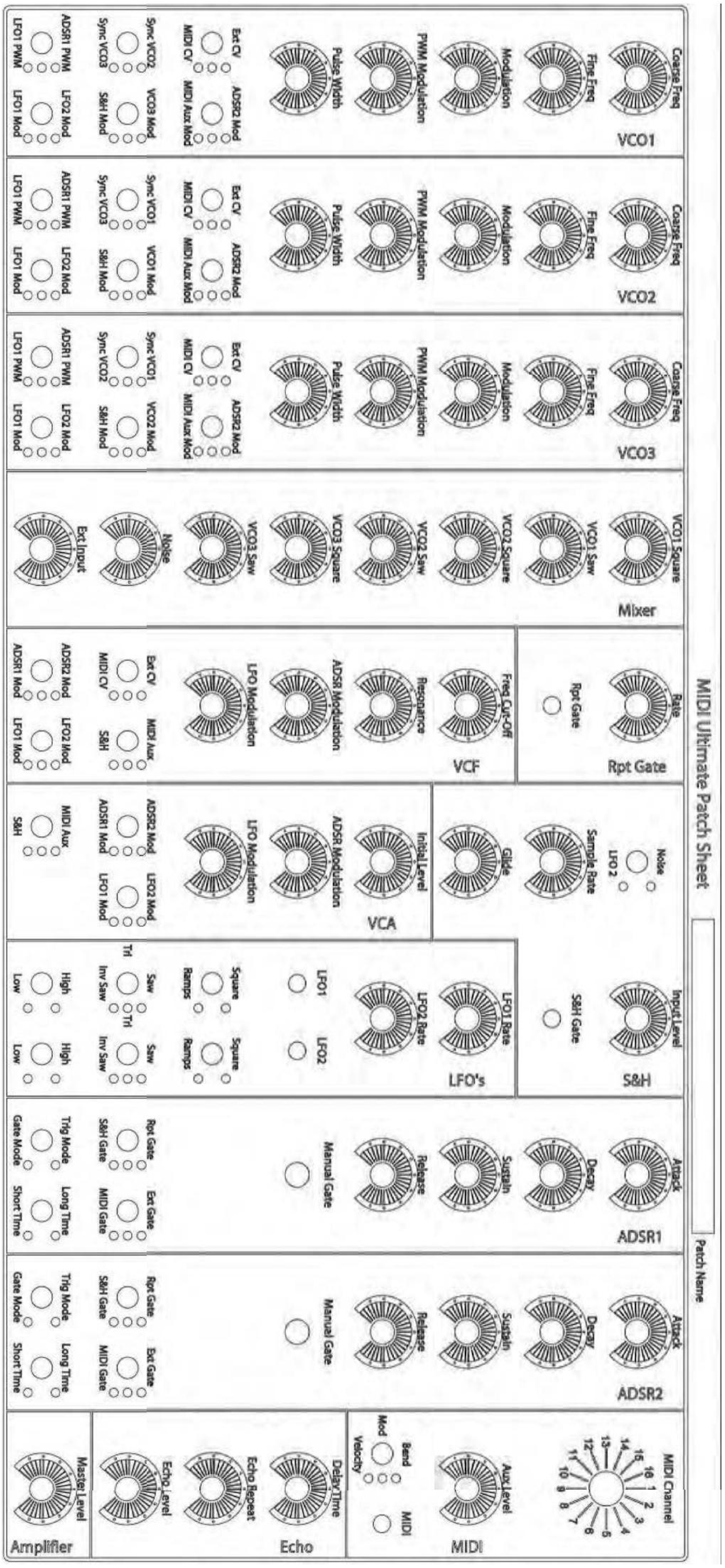
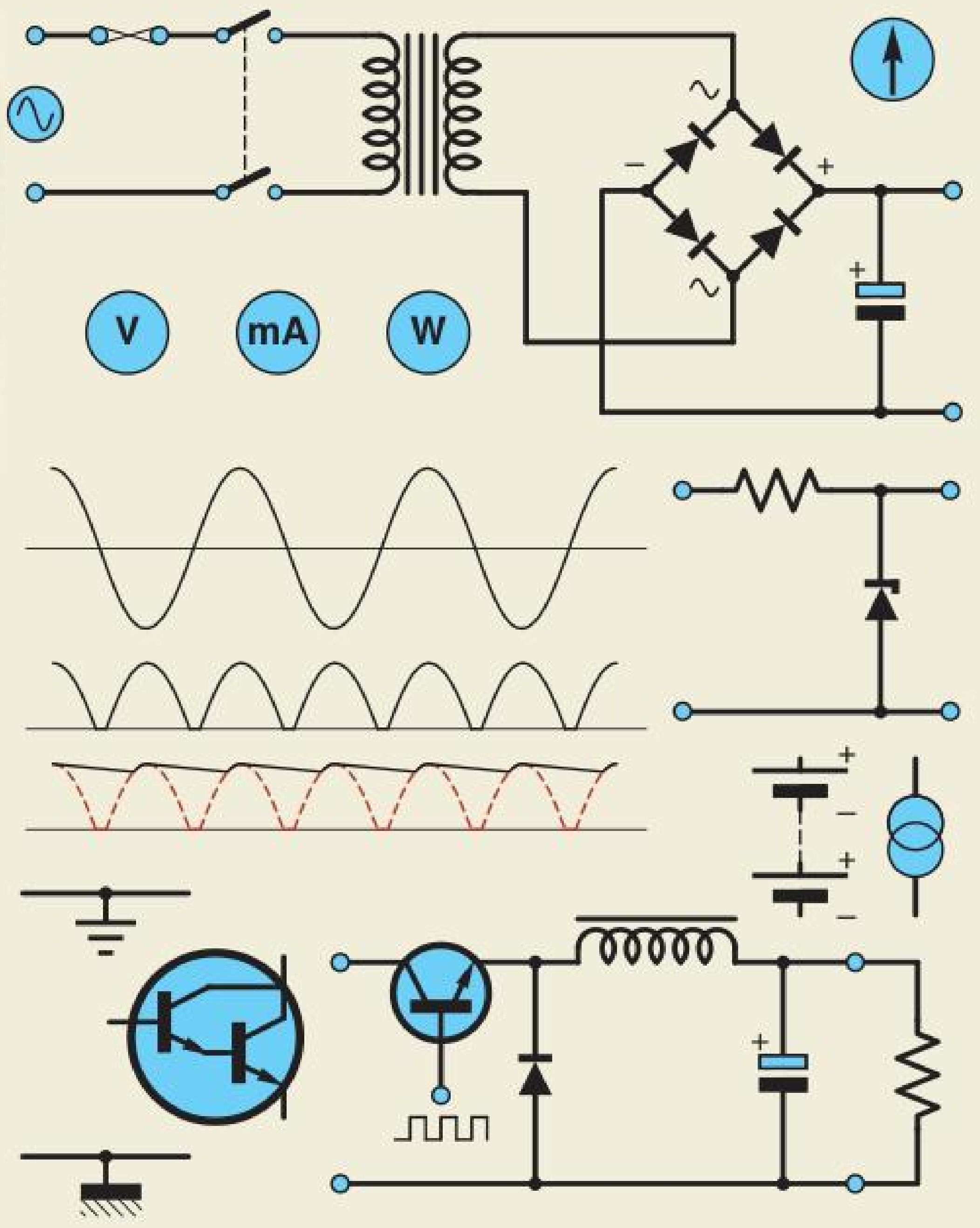

MIDI Ultimate Patch Sheet
Patch Name
VCO1
Coarse Freq
Fine Freq
Modulation
PWM Modulation
Pulse Width
Ext CV
ADSR2 Mod
MIDI CV
MIDI Aux Mod
Sync VCO2
VCO3 Mod
Sync VCO3
S&H Mod
ADSR1 PWM
LFO2 Mod
LFO1 PWM
LFO1 Mod
VCO2
Sync VCO1
VCO1 Mod
VCO3
VCO2 Mod
Sync VCO2
Mixer
VCO1 Square
VCO1 Saw
VCO2 Square
VCO2 Saw
VCO3 Square
VCO3 Saw
Noise
Ext Input
Rpt Gate
Rate
VCF
Freq Cut-Off
Resonance
ADSR Modulation
LFO Modulation
MIDI Aux
S&H
ADSR1 Mod
Noise
LFO 2
Sample Rate
Glide
VCA
Initial Level
S&H
Input Level
S&H Gate
LFO's
LFO1 Rate
LFO2 Rate
LFO1
LFO2
Square
Ramps
Saw
Inv Saw
Tri
High
Low
ADSR1
Attack
Decay
Sustain
Release
Manual Gate
Rpt Gate
Ext Gate
S&H Gate
MIDI Gate
Trig Mode
Long Time
Gate Mode
Short Time
ADSR2
MIDI
MIDI Channel
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Aux Level
Bend
Mod
Velocity
Echo
Delay Time
Echo Repeat
Echo Level
Amplifier
Master Level

Fig.102. This blank patch sheet is available at soundtronics.co.uk and the *PE* website.

Teach-In 2019

Powering Electronics

Part 8: Batteries



by Mike Tooley

Your latest project is finished and it's ready to go, but the job isn't done until you've found an appropriate source of power. This can be as trivial as locating a suitably rated mains adapter or as complex as designing a switched-mode power supply with multiple outputs and battery backup. Our latest *Teach-In* series is here to help, and it will provide you with an insight into all things power-related.

Last month, we examined some simple arrangements for producing negative outputs from a positive DC supply and managing the safe dissipation of heat. This month, we will be bringing the series to a conclusion by taking a detailed look at battery types, characteristics, applications, and the precautions necessary when using the latest generation of high-energy Li-ion and LiPo cells. We also provide some useful advice on constructing inductors for use in noise filters and SMPS power supplies generally.

Our *Teach-In 2019 Practical Project* is a simple battery monitor that will indicate the state of charge or discharge of battery packs supplying nominal output voltages between 9V and 15V. Finally, we conclude the *Powering Electronics Teach-In* 2019 series with a comprehensive index.

Batteries

Batteries are an ideal power source for small, lightweight and portable items of electronic equipment. They can also be useful as a back-up supply that can be brought into service when a primary supply (such as the AC mains) should fail.

Batteries are energy storage devices that convert electrical energy to chemical energy (when being *charged*) and chemical energy to electrical energy (when being *discharged*). Batteries are composed of individual *cells*, which have voltages of between 1.2V and 3.7V. So, battery packs are made from several series-connected cells in order to provide a larger output voltage than would be available from a single cell (see Fig.8.1).

Primary and secondary cells

Cells fall into one of two principal categories; *primary* cells, which end their useful life when their chemical constituents are exhausted, or *secondary* cells (in which the chemical reaction may be reversed) which can be recharged many times. Alkaline (and older Leclanché cells) are examples of the former type, while nickel cadmium (Ni-Cd) and nickel-metal hydride (Ni-MH) cells are an example of the latter.

Capacity

The capacity of a battery is the amount of electrical energy that it can deliver and is simply the product of its rated discharge current (A) and rated discharge time (hours). Capacity is normally quoted in ampere-hours (Ah) or milliampere-hours (mAh). The capacity of a battery is somewhat dependent upon the rate of discharge and thus, to be strictly meaningful, the ampere-hour rate should be specified for a stated discharge rate (eg, 2,500mAh for a discharge current of 500mA over a five-hour period). Depending upon the application envisaged, cells are often rated for discharge periods of between two and 16 hours.

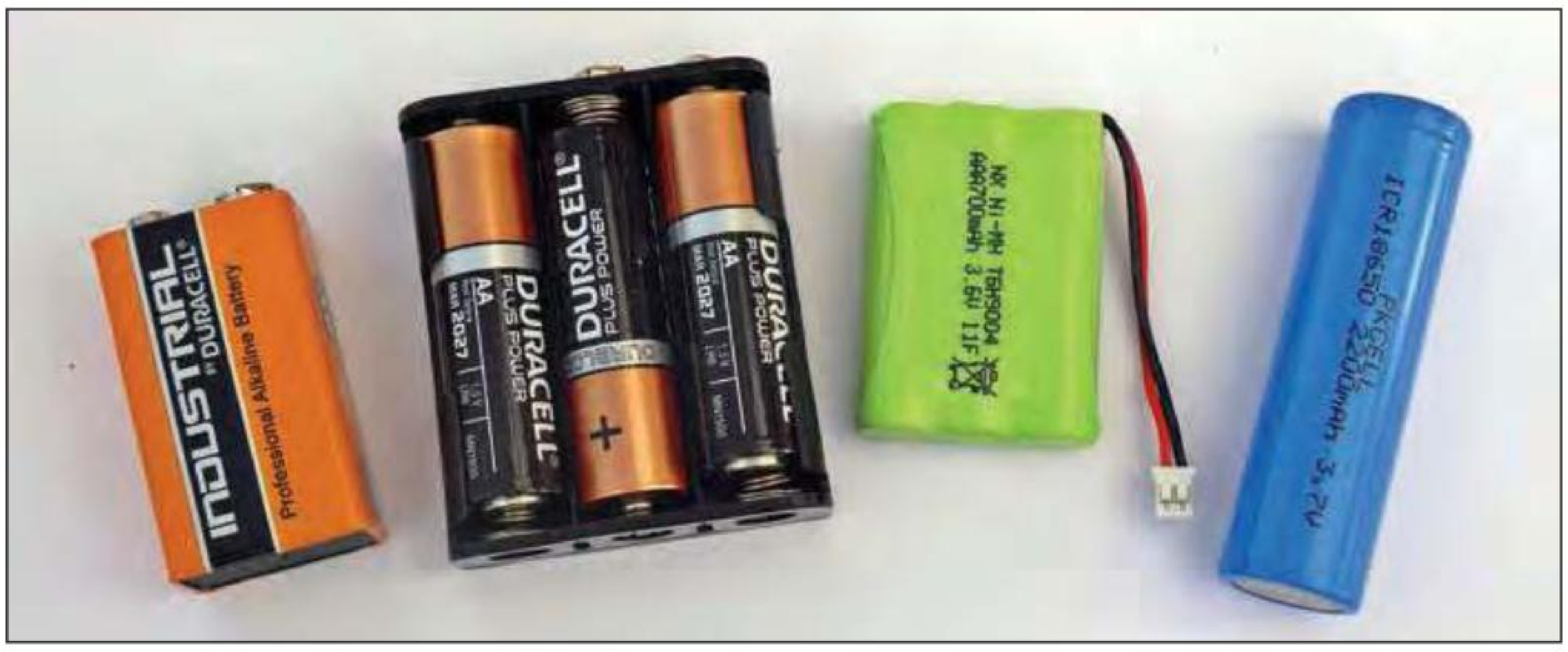


Fig.8.1. Some typical battery packs for small electronic equipment. From left to right: alkaline, a 9V PP3 based on six layered 1.5V cells; a 4.5V battery pack based on three 1.5V alkaline cells; a 3.6V pack based on three Ni-MH cells; a single 3.7V high-capacity Li-ion cell.

Example 1

A nickel cadmium (Ni-Cd) battery is rated at 4.8Ah for a six-hour discharge period and it comprises ten individual series-connected cells (each having a nominal discharge voltage of 1.2V). The terminal voltage of the battery will be 10 × 1.2V or 12V and the energy content of the battery can be calculated from:

$$\text{Energy content} = 4.8\text{Ah} \times 12\text{V} = 57.6\text{AVh} = 57.6\text{Wh}$$

The battery should be capable of delivering an average load current of 4.8/6 = 0.8A over a continuous six-hour period.

Example 2
If the battery in Example 1 requires fourteen hours to charge at a terminal voltage of 13.5V and at a constant current of 0.4A the energy required to charge is (13.5 × 0.4 × 14) = 75.6Wh. The battery's watt-hour efficiency, expressed as a percentage, will thus be (57.6/75.6) × 100 = 76%.

Energy content

The energy content of a battery is specified in watt-hours (Wh) and is the product of the cell's capacity (Ah) and the average cell voltage (V) when being discharged. It's worth illustrating this – see Example 1.

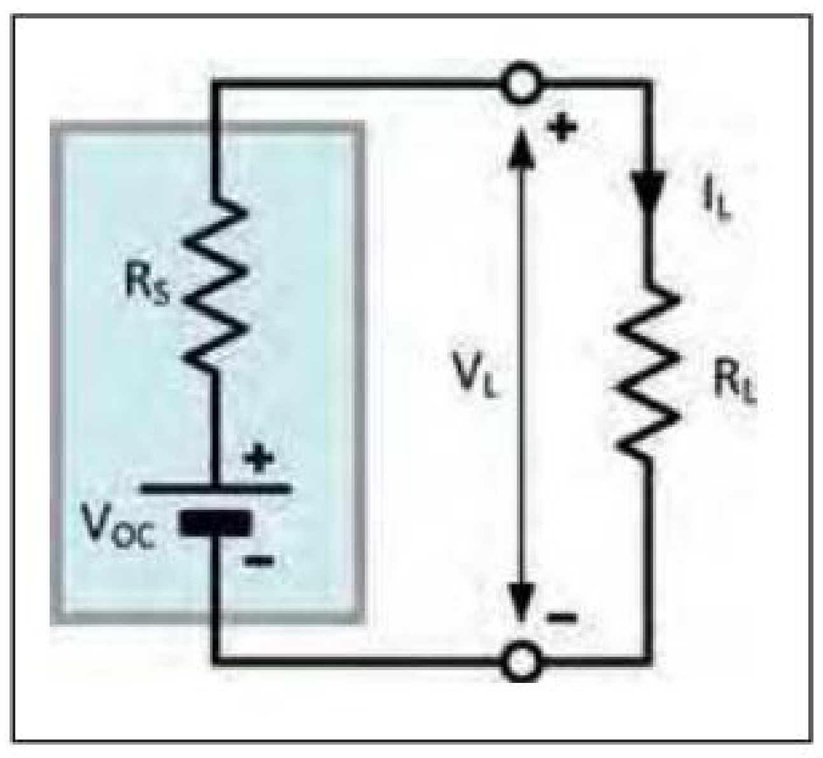


Fig.8.2. Internal resistance of a battery.

Efficiency

The watt-hour efficiency of a battery is the ratio of the energy realised upon discharge to that which is required to fully charge the battery. Example 2 shows how this works.

Example 3
A 3.6V Ni-MH battery pack produces an output voltage of 3.7V off load, falling to 3.5V when supplying a load current of 400mA. The internal resistance (R_S) of the battery can be determined from:

$R_S = V_{LOSS}/I_L = (3.7 - 3.5)/0.4 = 0.5\Omega$

When this battery is supplying a load current of 1A, the output voltage will fall to:

$V_L = 3.7 - (1 \times 0.5) = 3.2\text{V}$

Internal resistance

The internal resistance of a battery appears in series with any load to which the battery is connected. Fig.8.2 shows how a real battery can be represented

Table 8.1 Comparison of battery types and characteristics (green = strength, red = weakness)

Feature	Alkaline	Nickel-cadmium (Ni-Cd)	Nickel-metal hydride (Ni-MH)	Sealed lead-acid (SLA)	Lithium-ion (Li-ion)	Li-ion polymer (LiPo)
Rechargeable?	No	Yes	Yes	Yes	Yes	Yes
Nominal cell voltage	1.5V	1.2V	1.2V	2V	3.7V	3.7V
Typical battery/pack configuration	3V, 4.5V, 6V, 9V (2, 3, 4, 6 cells)	3.6V (3 cells)	3.6V (3 cells)	6V or 12V (3 or 6 cells)	7.2V (2 cells)	7.2V (2 cells)
Energy density (Wh/kg)	80	45 to 80	60 to 120	30 to 50	110 to 160	100 to 130
Typical cycle life	n/a	800 to 1200	300 to 500	200 to 300	500 to 1000	300 to 500
Typical fast charge time	n/a	1 to 2 hours	2 to 4 hours	8 to 16 hours	2 to 4 hours	2 to 4 hours
Overcharge tolerance	n/a	Moderate	Low	High	Very low	Low
Self-discharge (per month)	Limited by shelf life	20%	30%	5%	10%	10%
Typical load current	C/20 to C/5	C/10 to C/2	C/10 to C/4	C/5	C/4 to C/2	C/4
Peak load current	C/2	>10C	5C	5C	>2C	>2C
Typical internal resistance (Ω)	0.5 to 2	0.15	0.25	<0.1	0.2	0.2 to 0.5
Operating temperature (°C)	0 to +65	–40 to +60	–20 to +60	–20 to +60	–20 to +60	0 to +60
Cost factor (relative to Ni-CD, SLA)	4 to 8	1.0	1.2 to 1.5	1.0	1.5 to 2.0	2.0 to 2.5
Advantages	Universally available in standard sizes	Rugged and economical	Less prone to memory effect and more environmentally friendly than Ni-Cd	Reliable and dependable; good performance at high discharge currents	Very high energy density; low self-discharge; no memory effect	Lightweight, compact and available in a wide range of form factors
Disadvantages	Uneconomic; unsuitable for high-current applications; limited shelf-life	Relatively low energy density vs Li-ion and LiPo; memory effect; environmentally unfriendly	Limited shelf-life; high self-discharge; poor performance at high temperatures	Relatively low energy density (bulky and heavy)	Requires protection circuitry; careful charging and care when using	Requires protection circuitry; careful charging and care when using; can be expensive

by a perfect voltage source connected in series with its internal resistance (R_S). When the battery is disconnected from its load, the voltage measured under open-circuit conditions (V_{OC}) will be identical to that of the perfect internal voltage source. However, when a load (R_L) is connected, the terminal voltage will fall by an amount equal to the voltage dropped across the internal resistance of the battery – thus:

$$V_L = V_{OC} - V_{LOSS}$$

where V_L is the terminal voltage of the battery (the potential difference that's effectively delivered to the load, R), V_{OC} is the open-circuit (no-load) battery voltage, and V_{LOSS} is the voltage dropped across the internal resistance of the battery (ie, the voltage 'lost' inside the battery).

Now, $V_{LOSS} = I_L \times R_S$, and so:

$$V_L = V_{OC} - (I_L \times R_S)$$

V_L, V_{OC} and I_L can be measured, and thus R_S can be obtained.

It should be noted that the internal resistance of a battery increases when the battery is in a discharged state. Furthermore, internal faults within a battery usually manifest themselves as a significant increase in internal resistance (which may then render the battery unserviceable). See Example 3 for an internal resistance calculation.

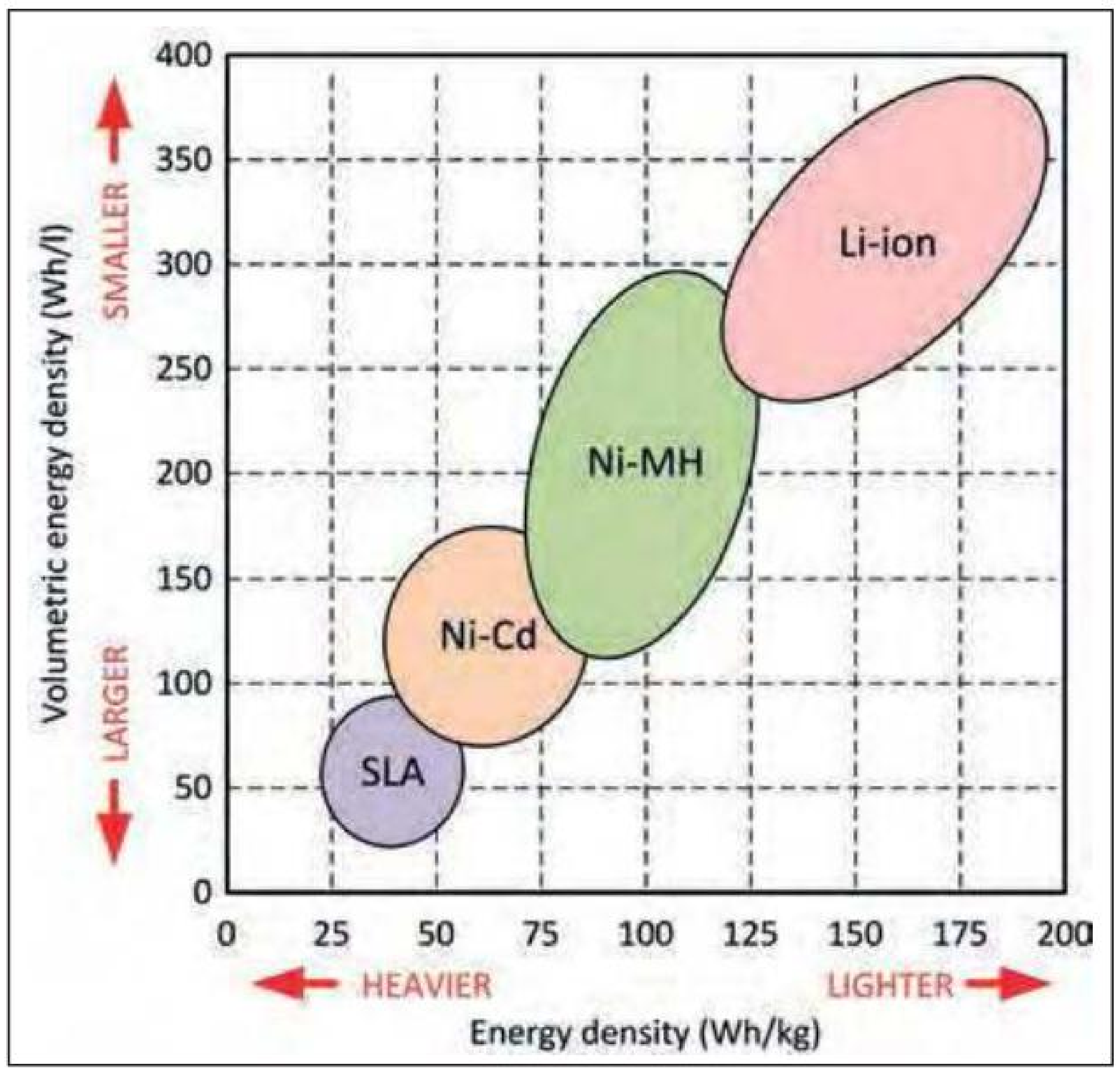


Fig.8.3. Comparison of the energy densities of various types of battery (note the relationship between energy, size and weight; and how Li-ion batteries are superior in both respects).

Battery types and characteristics

There's a vast and somewhat bewildering range of batteries available to the electronic equipment designer, and the choice of a suitable battery type can often be crucial to deriving optimum performance from the equipment. Furthermore, the choice of battery type is invariably a compromise, taking into account factors such as capacity, energy content, efficiency, operational life and cost (see Table 8.1). Before we move on it's worth briefly discussing the characteristics and applications of each of the battery types – summarised in Table 8.1.

Alkaline batteries

Alkaline batteries are universally available on almost every high street. Individual cells have a nominal terminal voltage of 1.5V (a fresh cell usually has a voltage of a little less than 1.6V, falling to about 1.25V at the end of the cell's working life). Alkaline cells are disposable and therefore not generally cost-effective in the long term. They can have appreciable values of quoted capacity (eg, 2800mAh for an AA battery) but this can be somewhat misleading as these battery types are only suitable for use at relatively low discharge rates. For example, when delivering a current of 1A, an AA cell may only be able to sustain this current for less than an hour, equivalent to a capacity of less than 700mAh.

Since alkaline cells are disposable, a particular concern is their self-discharge rate, which imposes limitations on their shelf life. A typical self-discharge rate for an alkaline battery is less than 3% per month and, although this might not sound problematic, after a twelve-month period of inactivity, an alkaline battery will have lost a significant proportion of its energy content. Alkaline cells are available at reasonably low cost in a very wide range of common sizes (including AAA, AA, C, D and PP3) – see Table 8.2.

Nickel-cadmium batteries

The terminal voltage of a single nickel-cadmium (Ni-cad or Ni-Cd) cell is usually assumed to be 1.2V; but, as with other types of cell, there's some variation during the discharge period. Unlike some other types of cell, nickel-cadmium ones exhibit a remarkably constant output voltage during discharge. After falling initially from approximately 1.3V, the cell voltage remains within about 5% of 1.25V for more than 75% of the discharge period. This makes Ni-Cd batteries ideal for use in equipment that doesn't have the benefit of an internal voltage regulator.

Nickel-cadmium cells exhibit an extremely low value of internal resistance and this makes them eminently suited to applications that demand the delivery of high currents for short periods. A notable disadvantage of Ni-Cd batteries (often referred to as 'memory effect') occurs when a battery exhibits a loss of capacity after being left in a partially charged state for a long period of time. Ni-Cd batteries benefit from regular (and full) charge/discharge cycles.

Nickel-metal hydride (Ni-MH)

Nickel-metal hydride batteries are more environmentally friendly than Ni-Cd and sealed lead-acid (SLA – see below) batteries yet still offer reasonably good energy density. Unfortunately, rates of self-discharge are higher than other types and the service life is reduced if a battery is subject to high loads. When compared with their Ni-Cd counterparts, Ni-MH batteries are much less prone to memory effect. Although Ni-MH cells are available in counterpart equivalents to the common alkaline and Ni-Cd cells listed in Table 8.2, they are not always interchangeable and require different charging regimes.

Sealed lead-acid batteries

Most readers will already be familiar with lead-acid batteries, which are universally fitted to cars. The individual cell voltage in a lead-acid battery is 2V, so six individual cells are connected in series within a standard 12V car battery and 12 cells are present within a high-

Table 8.2 Commonly available alkaline batteries

Battery type	Nominal voltage (V)	Typical capacity, C (mAh)	Recommended discharge rate	Recommended average load current (mA)	Construction	Dimensions (mm)	Typical weight (kg)
AAA, LR03	1.5	1,100	0.017C	10 to 50	Cylindrical	10.5 × 44.5	0.011
AA, LR6	1.5	2,800	0.007C	20 to 100	Cylindrical	14.5 × 50.5	0.024
C, LR14	1.5	7,000	0.005C	40 to 250	Cylindrical	26.2 × 50	0.065
D, R20	1.5	17,000	0.002C	200 to 500	Cylindrical	34.2 × 61.5	0.13
PP3, 6LR61	9	570	0.025C	5 to 30	Rectangular (layered)	48.5 × 26.5 × 17.5 (H×L×W)	0.046

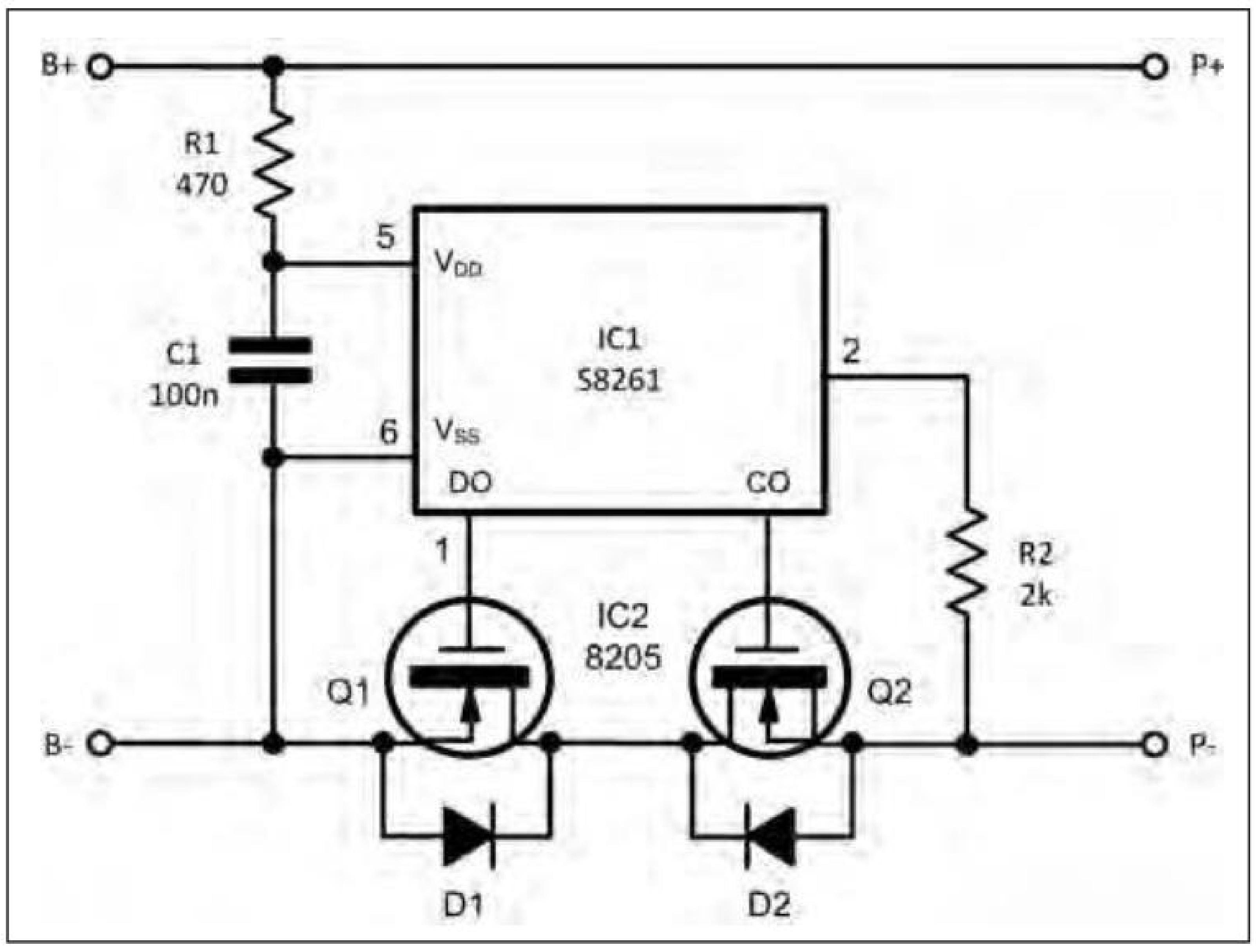


Fig.8.4. A typical Li-ion/LiPo battery protection circuit.

Parameter	Condition	Specification
Voltage	Nominal charging voltage	4.2V
Current	Maximum discharging current	4A
Over-charge protection	Detection voltage	4.25V
	Release voltage	4.1V
	Delay time	0.3 to 2s
Over-discharge protection	Detection voltage	3.0V
	Release voltage	3.2V
	Delay time	0.03 to 0.2s

Table 8.3 Li-ion/LiPo battery protection circuit specification

capacity 24V lorry battery. Smaller, lower capacity sealed lead-acid (SLA) batteries can often be an extremely cost-effective choice when a high-current supply is required for electronic equipment.

SLA batteries contain extremely toxic materials and great care is needed with their disposal. SLA batteries are ideal for use in applications where they can be left float-charging for long periods before discharging at a high-current for a relatively short period. Typical applications are emergency lighting, engine starting and uninterruptible power supplies (UPS). SLA batteries are usually rated for use at 0.2C (a five-hour discharge period). On the downside, when compared with other battery types, SLA batteries exhibit relatively poor energy densities.

Lithium ion (Li-ion)

Lithium-ion batteries perform well in terms of both capacity and energy density (see Fig.8.3). They also produce output voltages that remain reasonably constant over the full discharge period. They do not suffer from memory effect and the relatively high cell voltage (3.7V) supports electronic equipment with batteries constructed from only a limited number of series-connected cells. In some cases, a single 3.7V 18650 Li-ion cell is all that's required for some small items of low-voltage electronic equipment.

Li-ion Polymer (LiPo)

Lithium polymer (LiPo) batteries have many of the advantages of Li-ion batteries, but in a much more flexible form factor. This allows batteries to be easily fitted into a very small space while offering capacities and energy densities that are similar (but not quite equal) to those of conventional cylindrical Li-ion batteries.

Li-ion and LiPo battery care and protection

The high energy content and low internal resistance of Li-ion and LiPo batteries demands extra care in their use. Rapidly over-charging or over-discharging this type of battery can result in a very real risk of fire and explosion. Because of this, it is essential to treat Li-ion and LiPo batteries with care. To reduce these risks, many batteries are fitted with internal battery protection circuitry. This limits the battery current and voltage during both charge and discharge.

A typical Li-ion cell protection circuit (see Fig.8.4) operates according to the specification in Table 8.3. Note how separate charge and discharge MOSFET switches (Q2 and Q1 respectively) are used to cut-off the battery if and when an over-charge or over-discharge condition is detected.

Cylindrical Li-ion batteries (like the commonly available 3.7V 18650 battery) are available both with and without integrated protection circuitry. Protected cells are preferred for most applications and unprotected cells (due to their high energy content) must be treated with caution. A practical point worth noting is that protected and unprotected cells have slightly different dimensions (see Fig.8.5) and this can sometimes cause problems when cells are to be fitted in off-the-shelf battery holders.

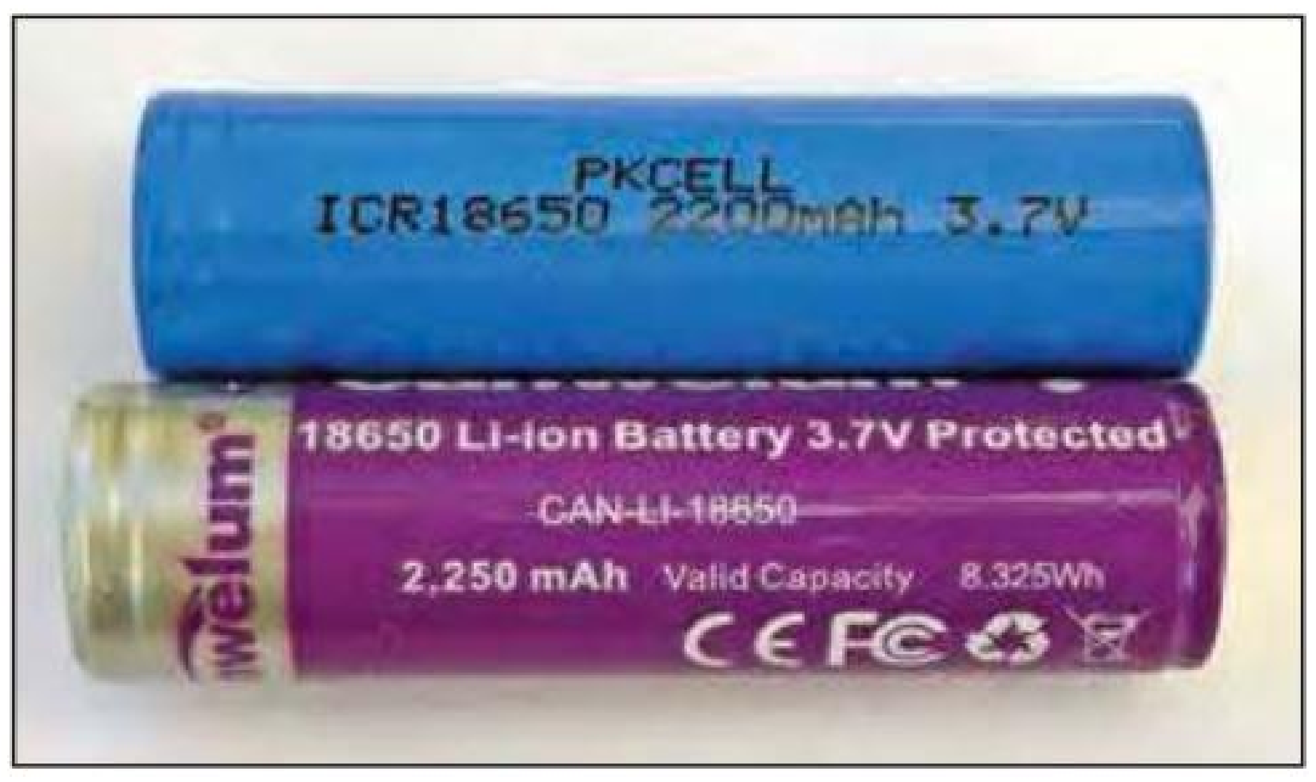

PKCELL
ICR18650 2200mAh 3.7V
18650 Li-ion Battery 3.7V Protected
CAN-LI-18650
2,250 mAh Valid Capacity 8.325Wh
weilum

Fig.8.5. Protected (bottom) and unprotected (top) 3.7V 18650 cells.

Charging Li-ion/LiPo batteries

Li-ion and LiPo cells and batteries need special charging arrangements and must *never* be charged using Ni-Cd or Ni-MH chargers. A typical single-cell Li-ion/LiPo charger is shown in Fig.8.6. The charging voltage is pre-set at 4.2V and the charging current (up to a maximum of 1A) is determined by the value of the programming resistor, R_{PROG}. IC1 automatically terminates the charge cycle when the charge current falls to 10% of the programmed value after the final float voltage is reached. The TP4056 chip (IC1) incorporates several other useful features, including a current monitor, under voltage lockout, automatic recharge and two status pins to indicate charge termination (pin-7) and the presence of an input voltage (pin-6).

The charger shown in Fig.8.6 operates with both a constant current (CC) and

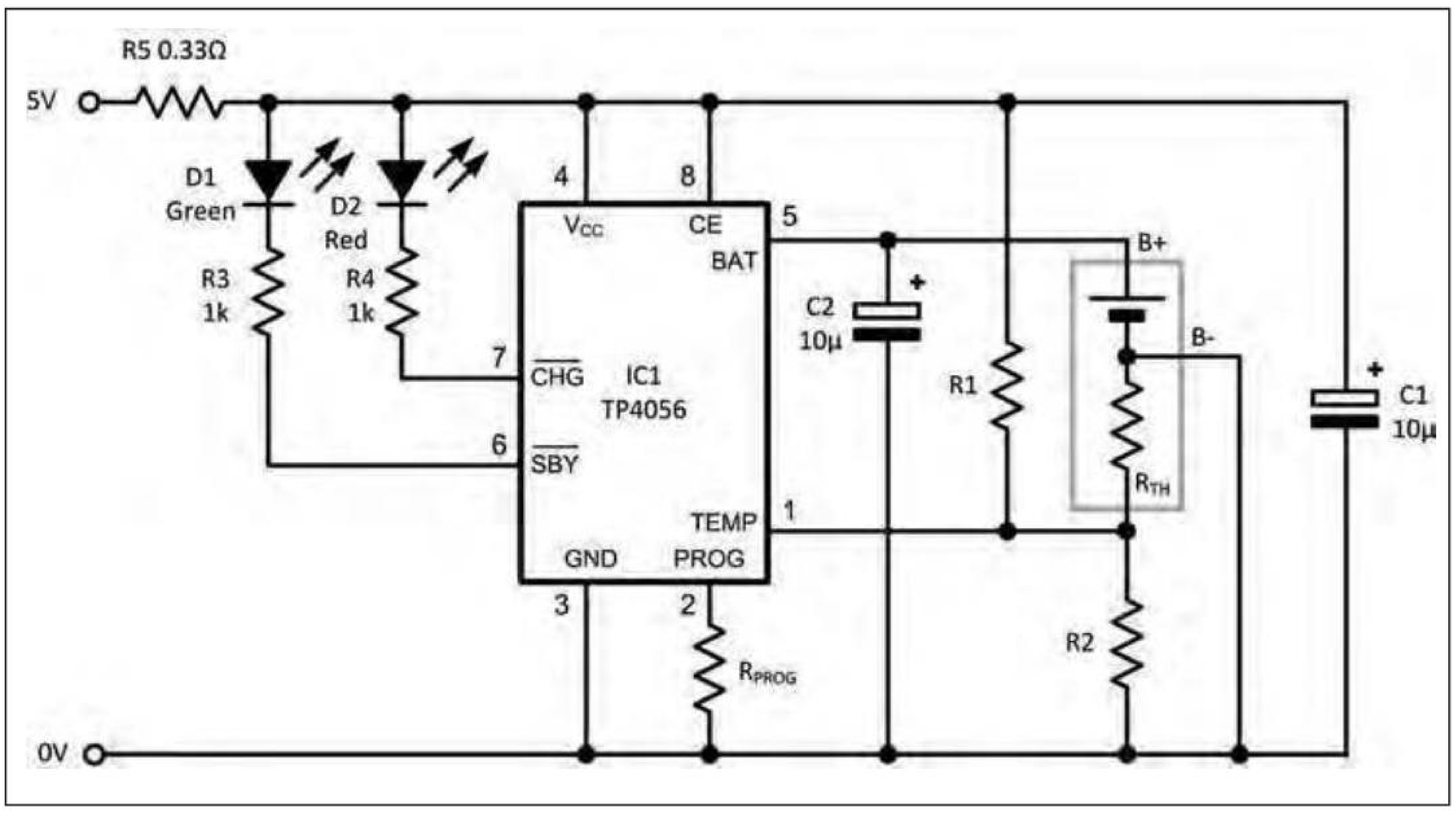


Fig.8.6. Circuit of a typical single-cell Li-ion/LiPo charger.

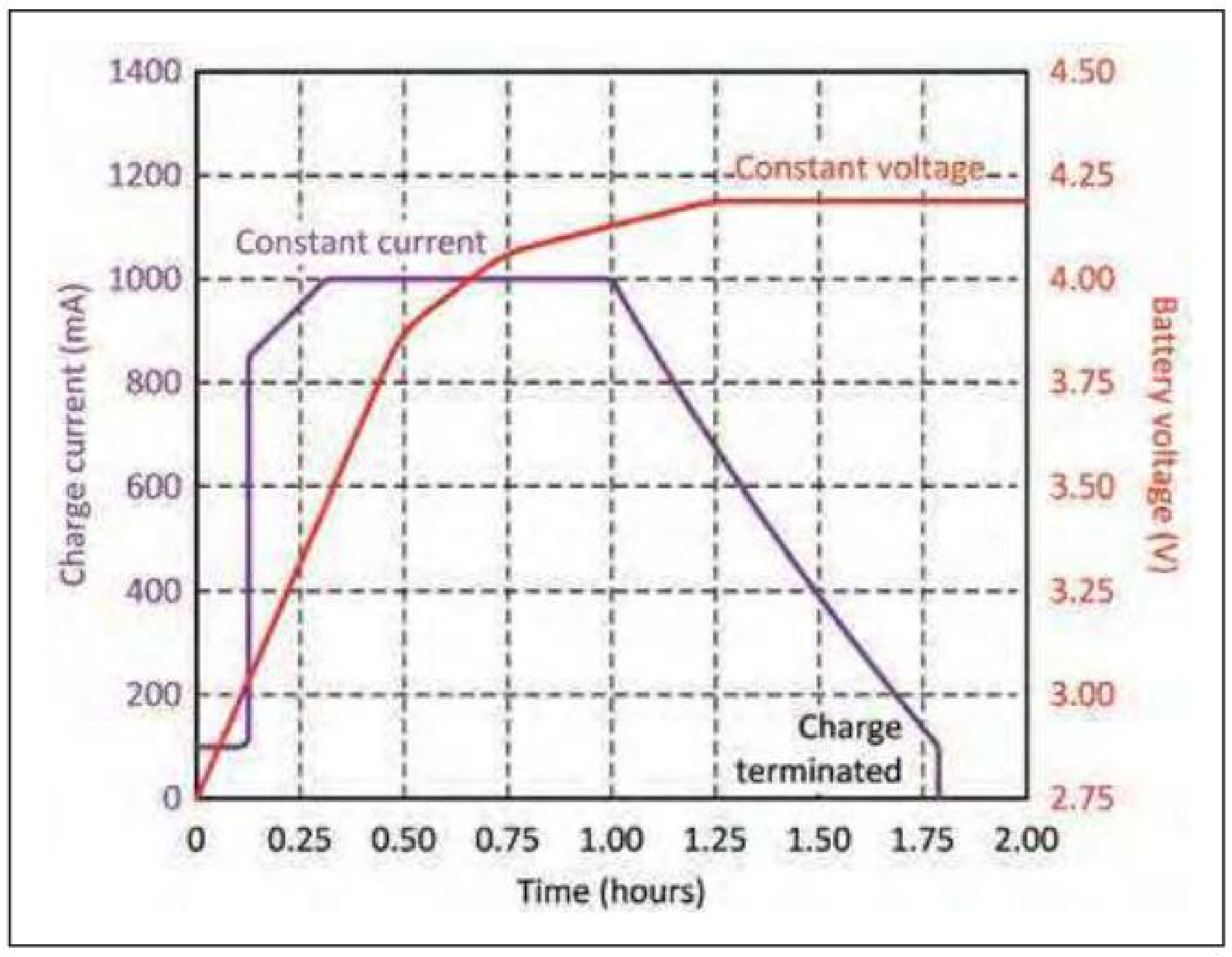


Fig.8.7. Typical Li-ion charging cycle (note that charging is completed within two hours).

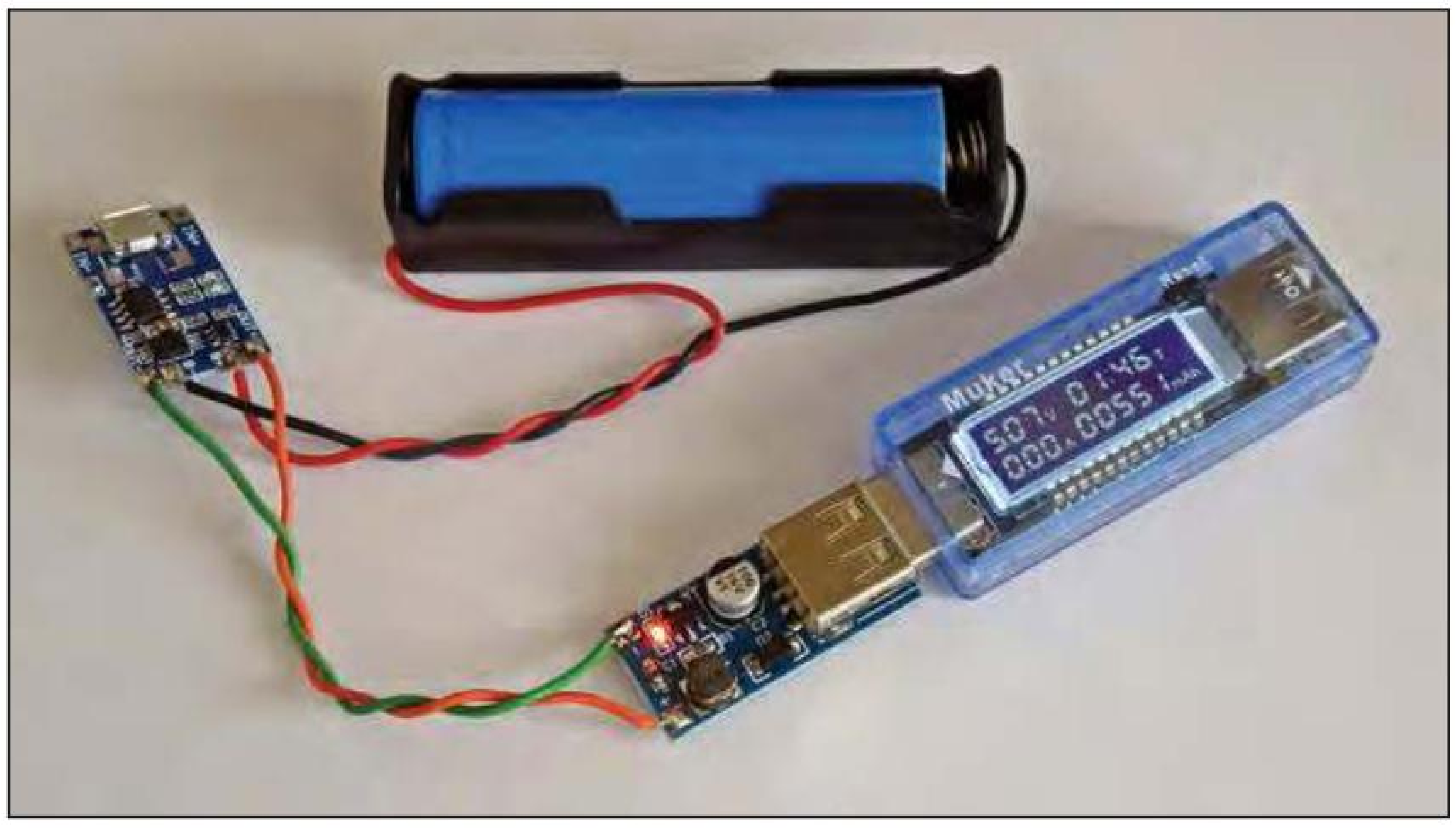


Fig.8.10. A USB UPS. From left to right: USB charge controller; unprotected 3.7V 18650 cell; discharge controller and voltage/current monitor.

Fig.8.8. A readily available two-cell 3.7V 18650 Li-ion battery charger.

constant voltage (CV) characteristic, as show in Fig.8.7. Note how the cycle begins with 10% of the programmed current delivered to the cell for a short period before the current increases to the programmed value for the remainder of the first half of the charging cycle during which CC conditions prevail. Thereafter, the charging current is progressively reduced as the charger enters CV mode. The cell voltage then reaches, and remains constant at 4.2V, and the cycle eventually terminates at the point at which the charging current falls to 10% of the programmed value.

It is important to be aware that, due to the exacting requirements of Li-ion and LiPo batteries, it is advisable to use off-the-shelf chargers rather than attempt to construct your own. A typical low-cost two-cell Li-ion battery charger is shown in Fig.8.8. This unit incorporates all of the features discussed earlier.

Using USB supplies

An alternative to using a dedicated Li-ion cell charger is that of using a standard 1A USB power supply. Together with a charge/discharge controller (see Fig.8.9) this can make an excellent uninterruptible 5V 1A DC supply (UPS). Fig.8.10 shows, from left to right, a USB charge controller, an unprotected 3.7V 18650 cell, and a discharge controller that uses SMPS boost technology to produce a stable 5V 1A DC output (being monitored using an off-the-shelf USB voltage/current tester).

Building batteries using LiPo cells

LiPo cells offer the distinct advantage that they are available in a huge range of capacities and form factors. This makes them ideal for fitting into a limited space and ensures performance that is vastly superior to the currently available Ni-MH alternatives. Fig.8.11 shows three 2800mAh LiPo batteries suitable for use in a series-connected configuration to realise a nominal 12V 2.8Ah battery. For safety, each cell is fitted with its own protection circuitry (see Fig.8.12) and the author's completed battery pack is shown in Fig.8.13 together with a similarly rated 12V SLA battery. Note how the LiPo pack is very much more compact than the SLA alternative! The discharge characteristics for the C/2 and

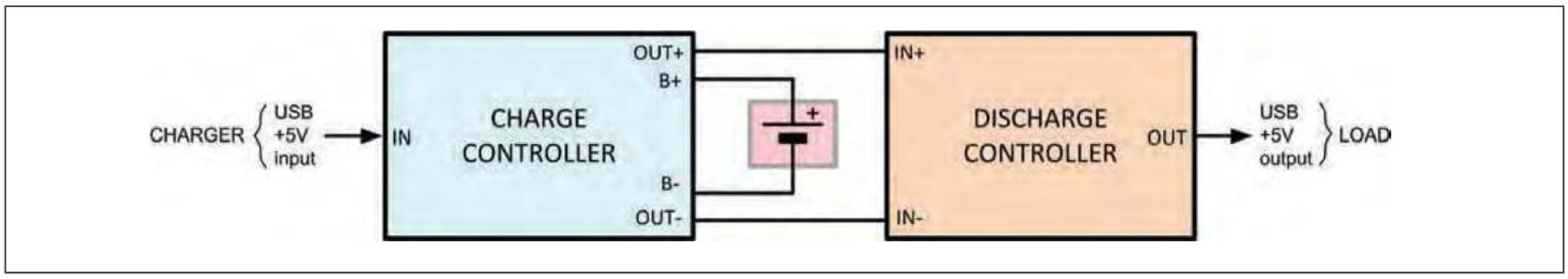


Fig.8.9. Basic elements of a 5V USB uninterruptible power supply (UPS).

Fig.8.11. Three low-cost LiPo batteries with form factors that are ideal for building into small items of portable electronic equipment.

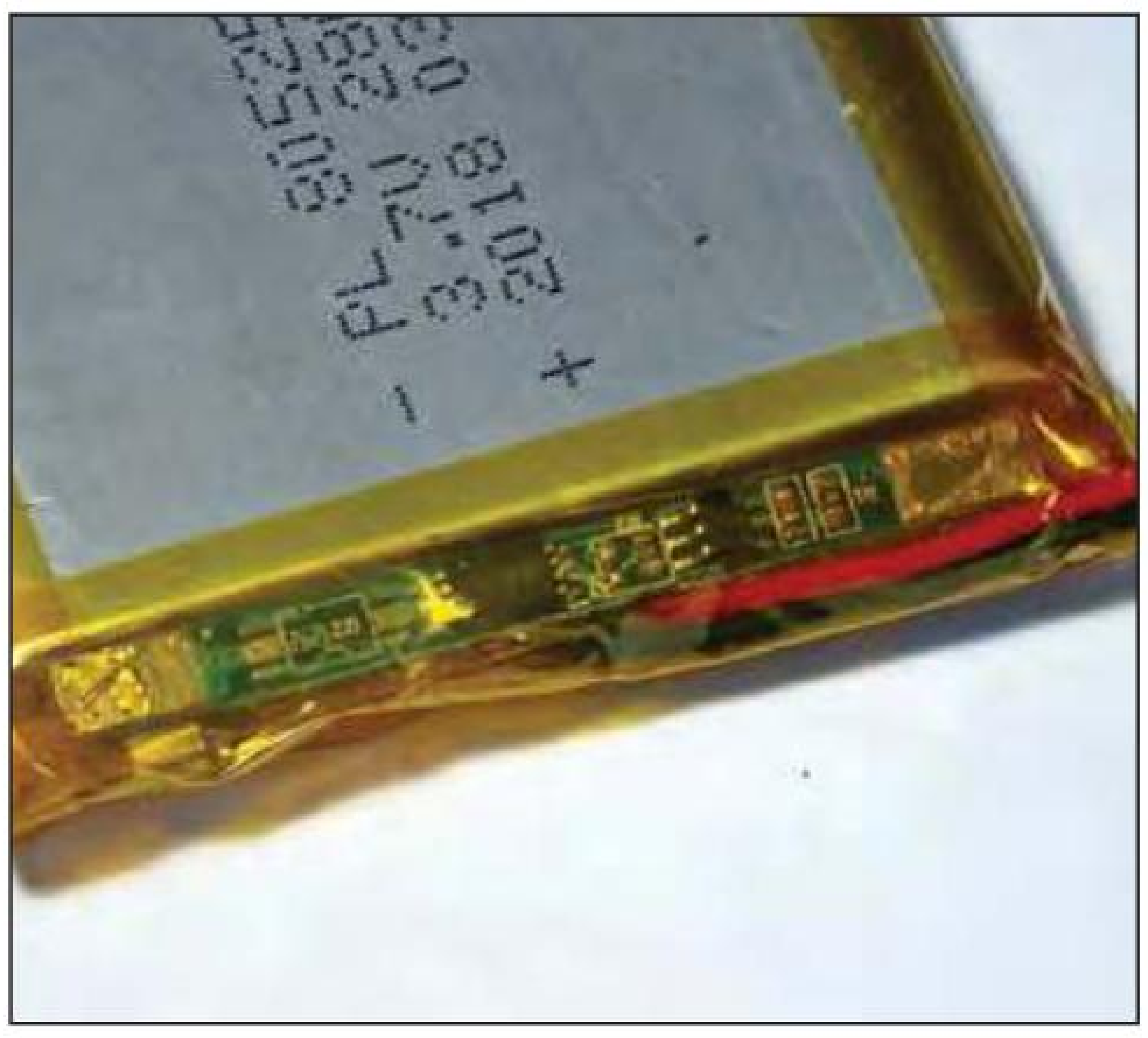


Fig.8.12. Each LiPo cell has its own integrated charge/discharge protection circuit.

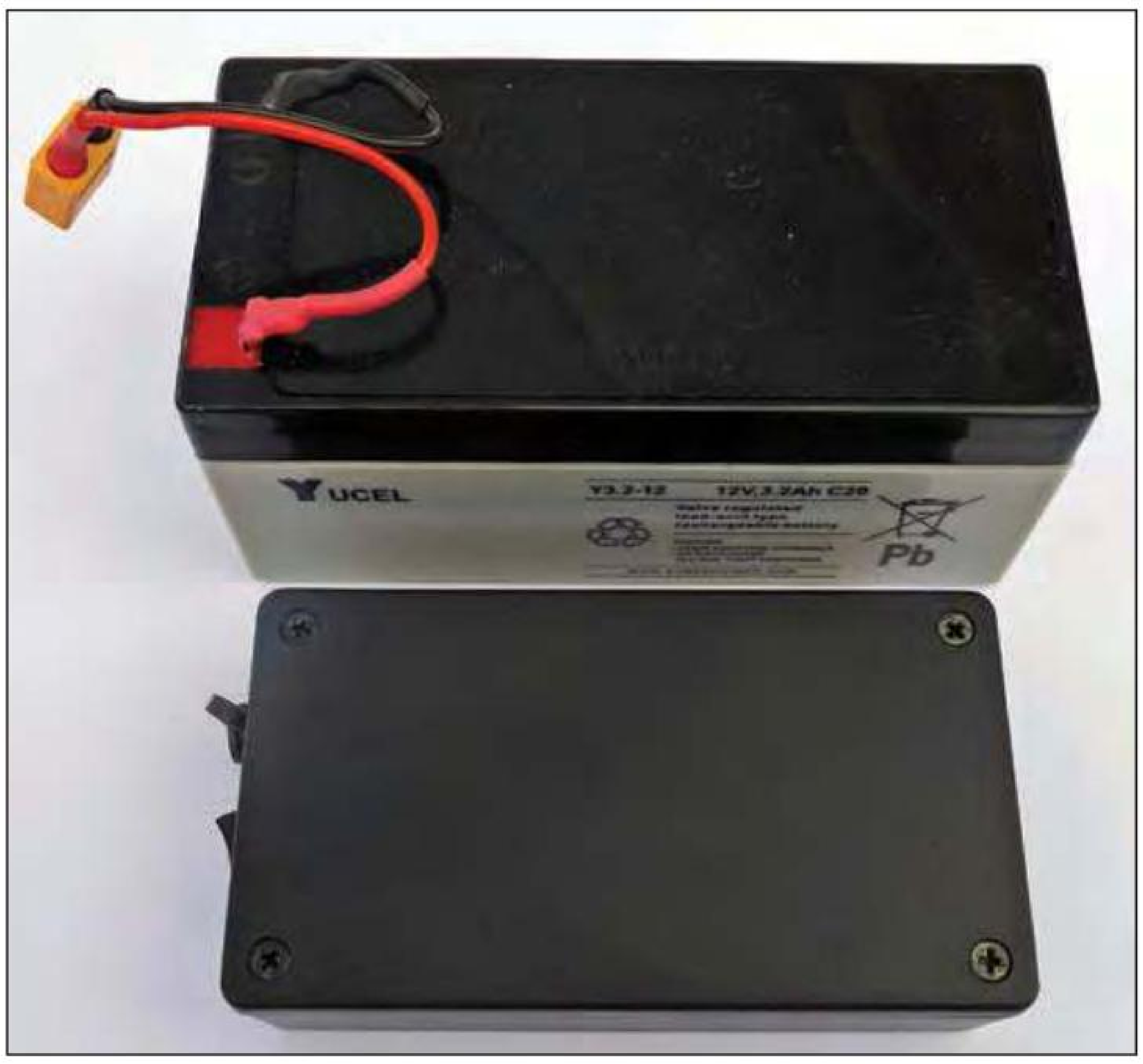


Fig.8.13. Similarly rated SLA (3.2Ah – top) and LiPo (2.8Ah – bottom) batteries. The author's battery pack uses three series-connected LiPo cells and is considerably more compact and lighter than the SLA battery.

C/10 discharge rates for the author's constructed three-cell LiPo pack are shown respectively in Fig.8.14 and 8.15.

Other types

In addition to the popular battery types listed earlier in Table 8.1 several other specialist battery types are available. Noteworthy amongst these are the tiny 1.5V and 3V alkaline manganese button cells that are ideal for supplying low-power MOS circuitry. Such cells can provide a compact alternative to AAA Ni-MH batteries, but at greater cost and with significantly reduced capacity.

Fig.8.14. C/2 discharge characteristic for the author's three-cell LiPo battery pack.

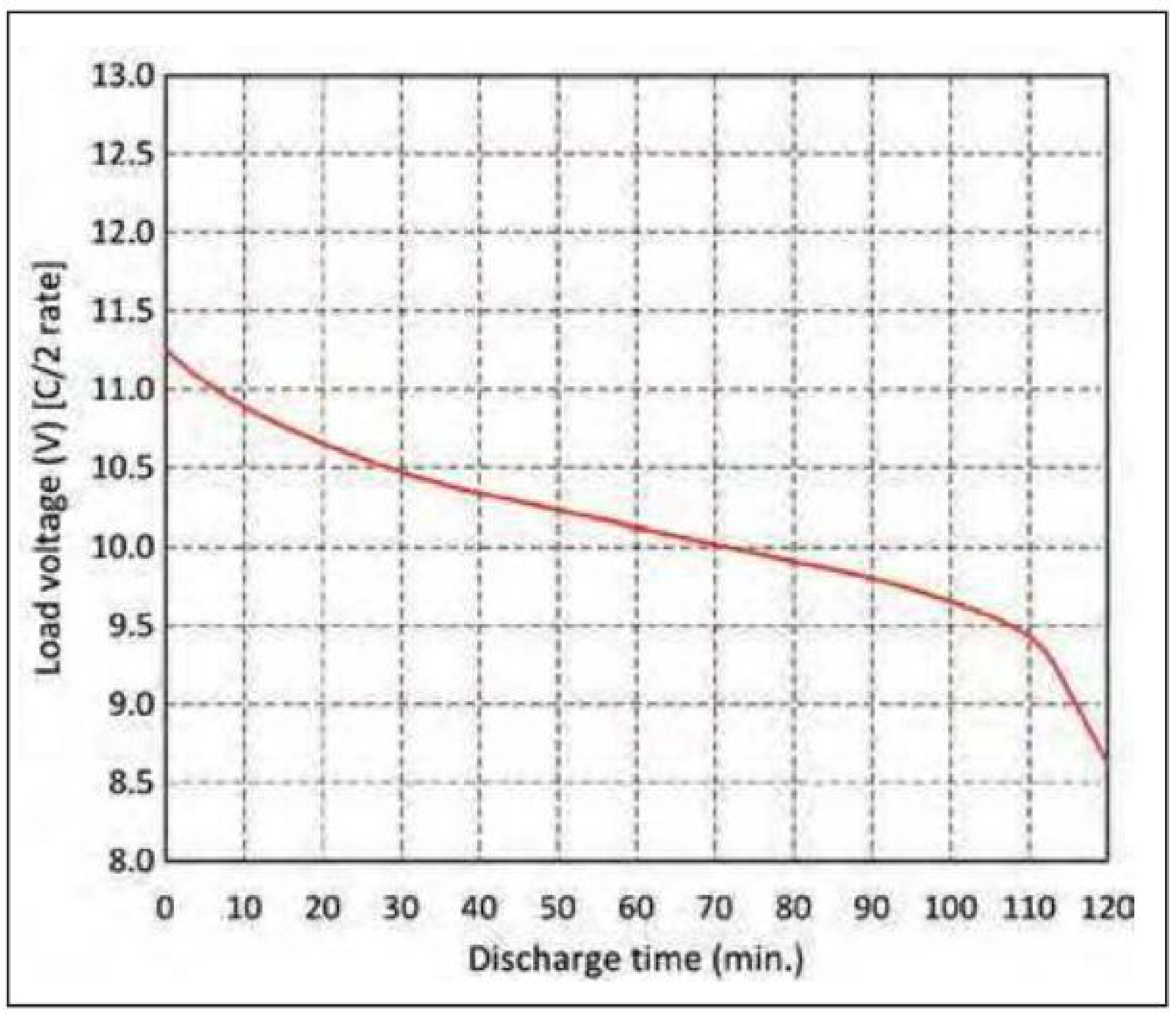
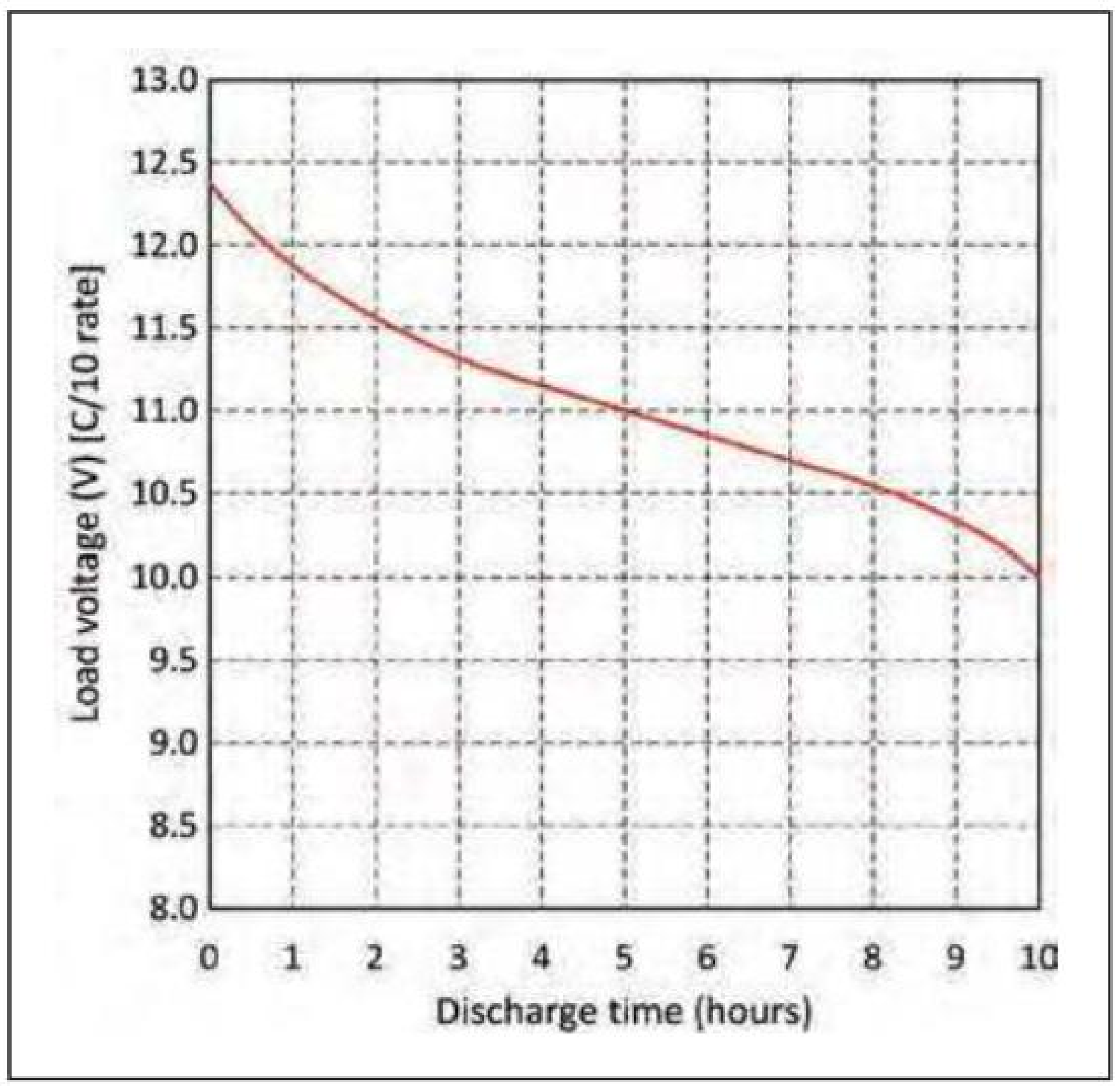


Fig.8.15. C/10 discharge characteristic for the author's three-cell LiPo battery pack.



Simple battery monitor

This month's *Practical Project* is a simple battery monitor that provides an indication of the status of a battery (or any other DC supply) with an output voltage in the range 5V to 15V. The specifications are as follows:

Input voltage ....9V to 15V (nominal)
Input current ....15mA (nominal)
Low threshold ....7V to 10V (typical)
High threshold................12V to 15V (typical)

The circuit of our *Simple battery monitor* is shown in Fig.8.16. The circuit uses a dual comparator arrangement (IC1) with pre-set potentiometers (RV1 and RV2) to set the high and low threshold voltages respectively. The supply voltage is in the normal range when only the red LED (D3) is illuminated. When neither of the LEDs are illuminated, the input voltage is below the set threshold voltage (typically indicating a need for battery replacement or recharging). When the blue LED (D2) is illuminated this indicates a high or over-voltage condition (requiring further investigation). See summary in Table 8.4.

Table 8.4 Battery conditions and corresponding indications

Blue LED (D2)	Red LED (D3)	Condition	Typical threshold voltage range	
			9V battery supply	12V battery supply
Off	Off	Battery low	Less than 7V	Less than 9.5V
Off	On	Battery normal	7V to 9.5V	9.5V to 13V
On	On	Charge or over-voltage condition	More than 9.5V	More than 14V

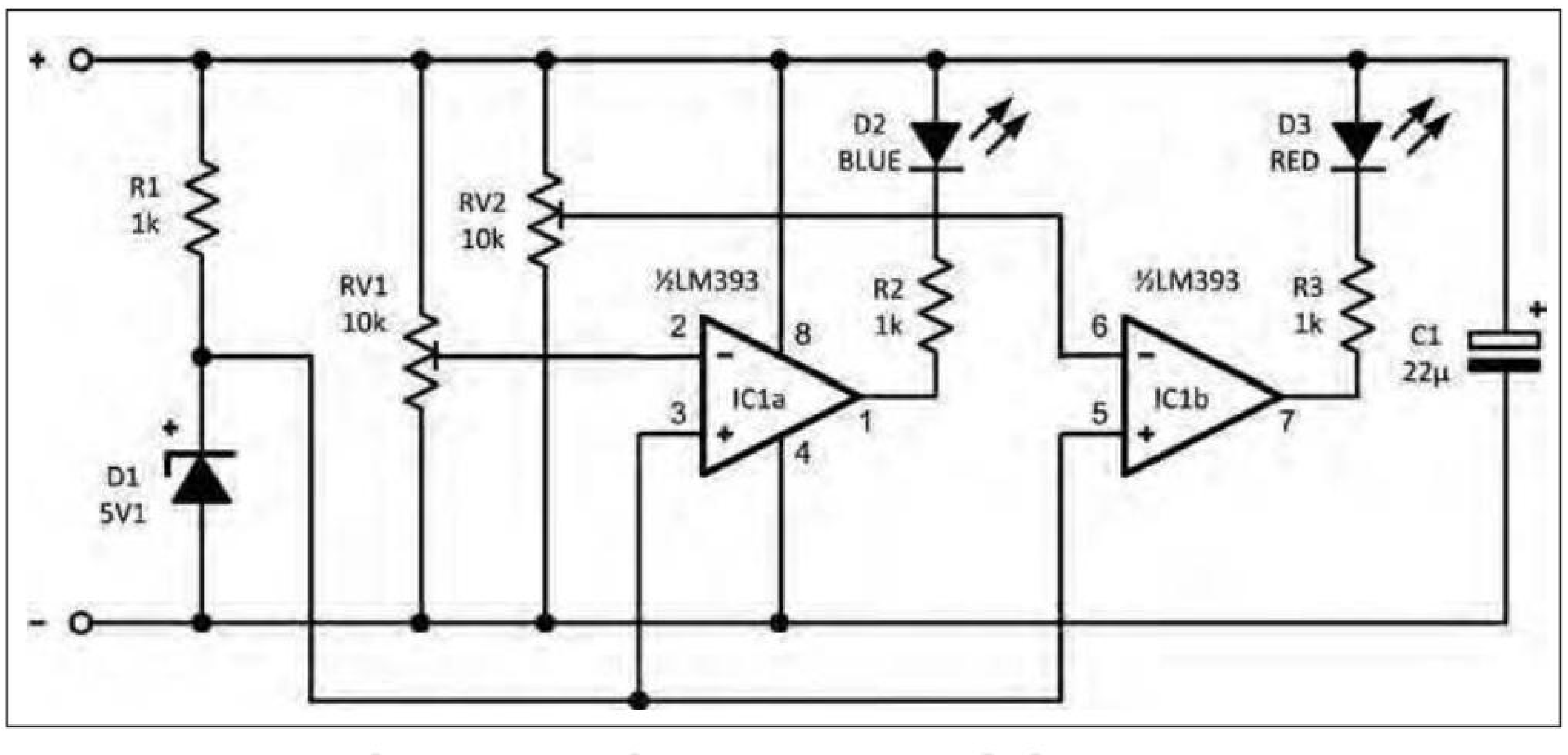


Fig.8.16. Our Teach-In Practical Project is a simple battery monitor.

You will need...

Perforated copper stripboard (9 strips each with 25 holes)
2 2-way PCB screw terminal connector (ST1 and ST2)
2 10kΩ miniature pre-set resistors (RV1 and RV2)
3 1kΩ resistors (R1, R2 ad R3)
1 22µF 35V capacitor (C1)
1 LM393 dual comparator (IC1)
1 Low-profile 8-pin DIL socket
1 5.1V Zener diode
1 Blue LED (D2)
1 Red LED (D3)
4 Stand-off pillars and mounting screws

Construction

The stripboard layout of the *Simple battery monitor* is shown in Fig.7.8.16. Note that there are 24 track breaks on the underside of the board and 13 links on the upper side. As always, once assembly is

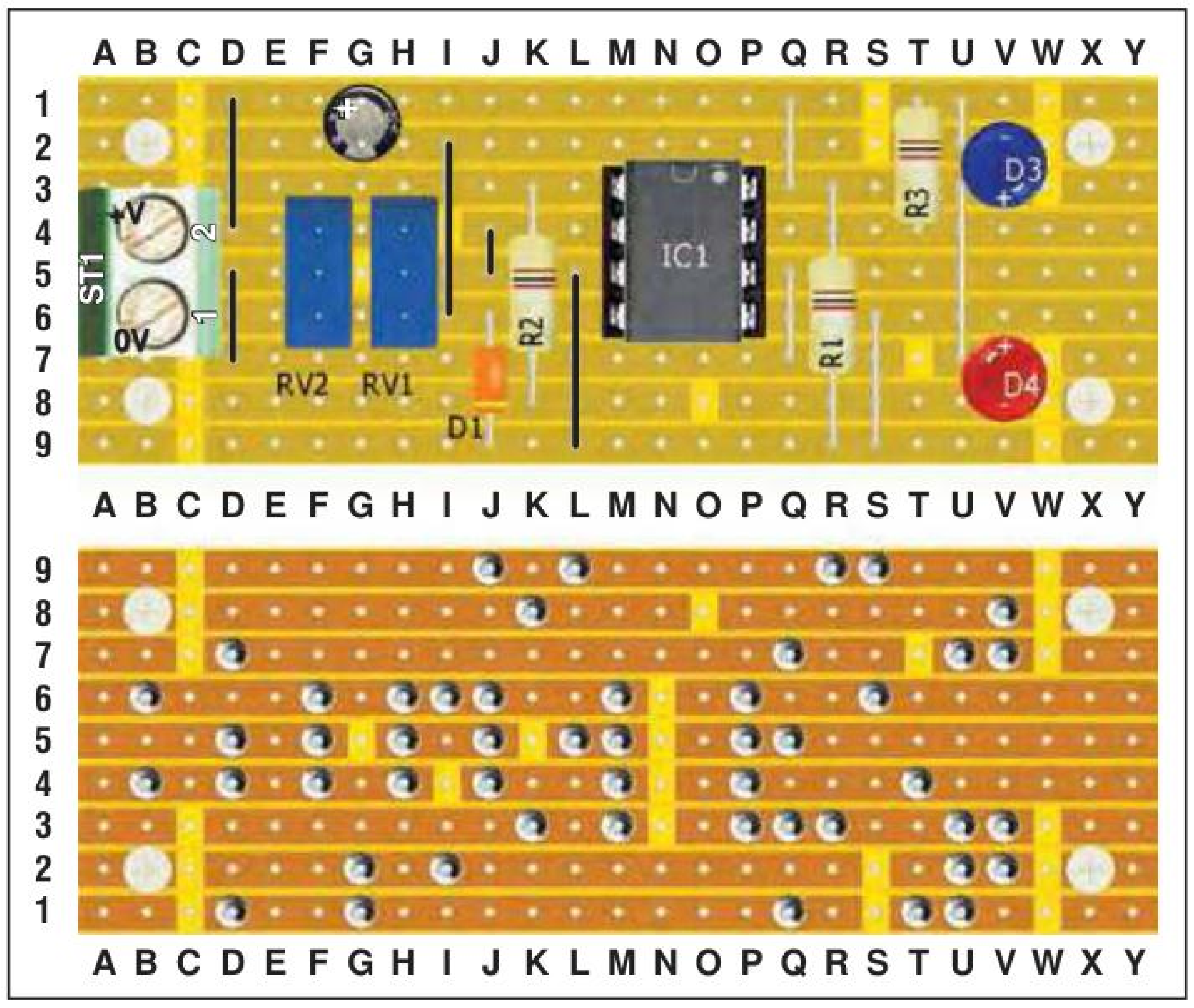

A B C D E F G H I J K L M N O P Q R S T U V W X Y
1 2 3 4 5 6 7 8 9
+V
0V
ST1
1
2
RV2
RV1
D1
R2
IC1
R1
R3
D3
D4
9 8 7 6 5 4 3 2 1

Fig.8.17. Stripboard layout of the simple battery monitor.

complete it is well worth carrying out a careful inspection of the circuit board, particularly checking the off-board wiring and links to ST1 and ST2.

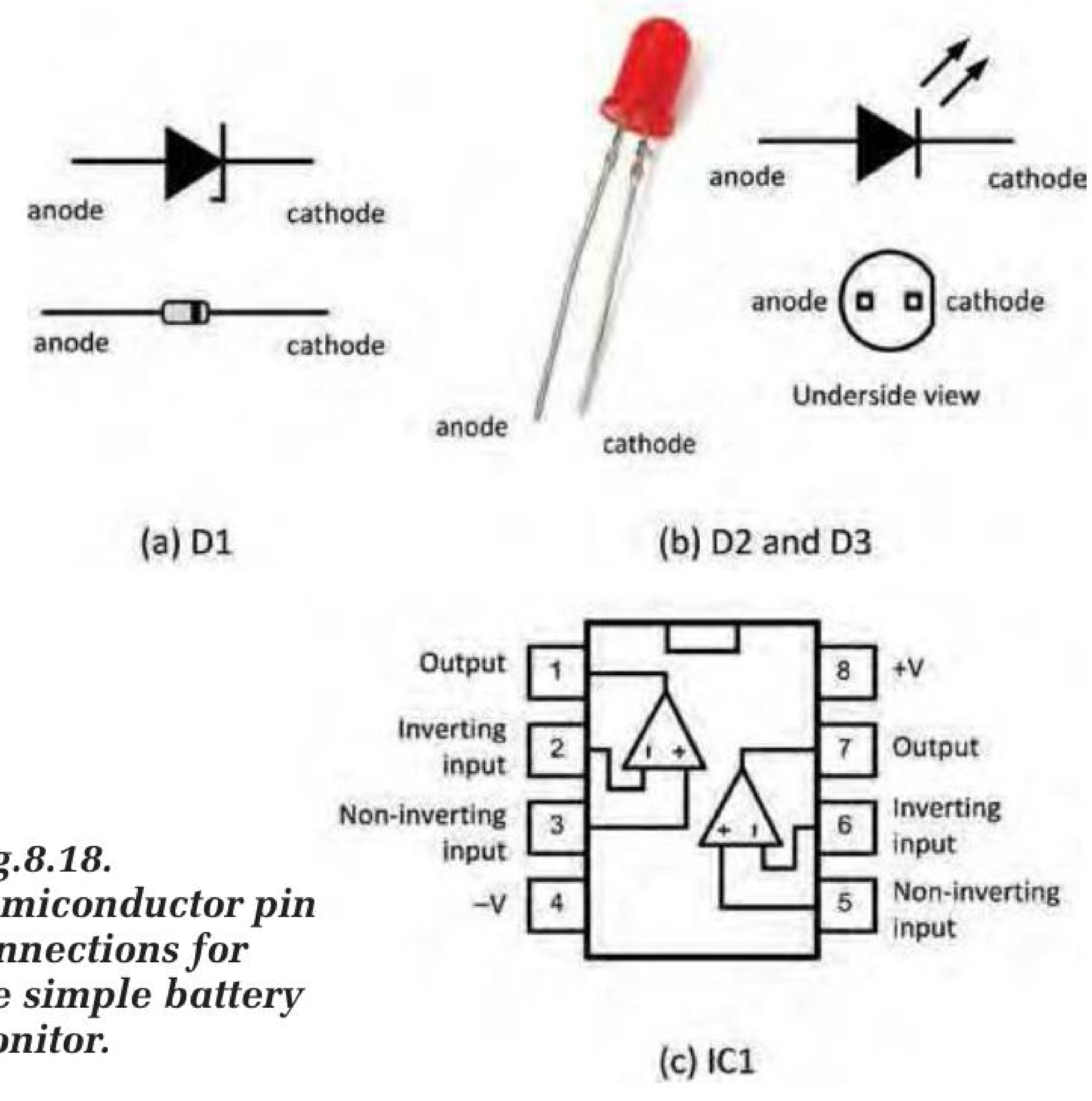

anode
cathode
anode
cathode
(a) D1
anode
cathode
anode
cathode
anode
cathode
Underside view
(b) D2 and D3
Output
Inverting input
Non-inverting input
–V
1
2
3
4
8
7
6
5
+V
Output
Inverting input
Non-inverting input
(c) IC1

Fig.8.18. Semiconductor pin connections for the simple battery monitor.

Get it Right! – Inductive components

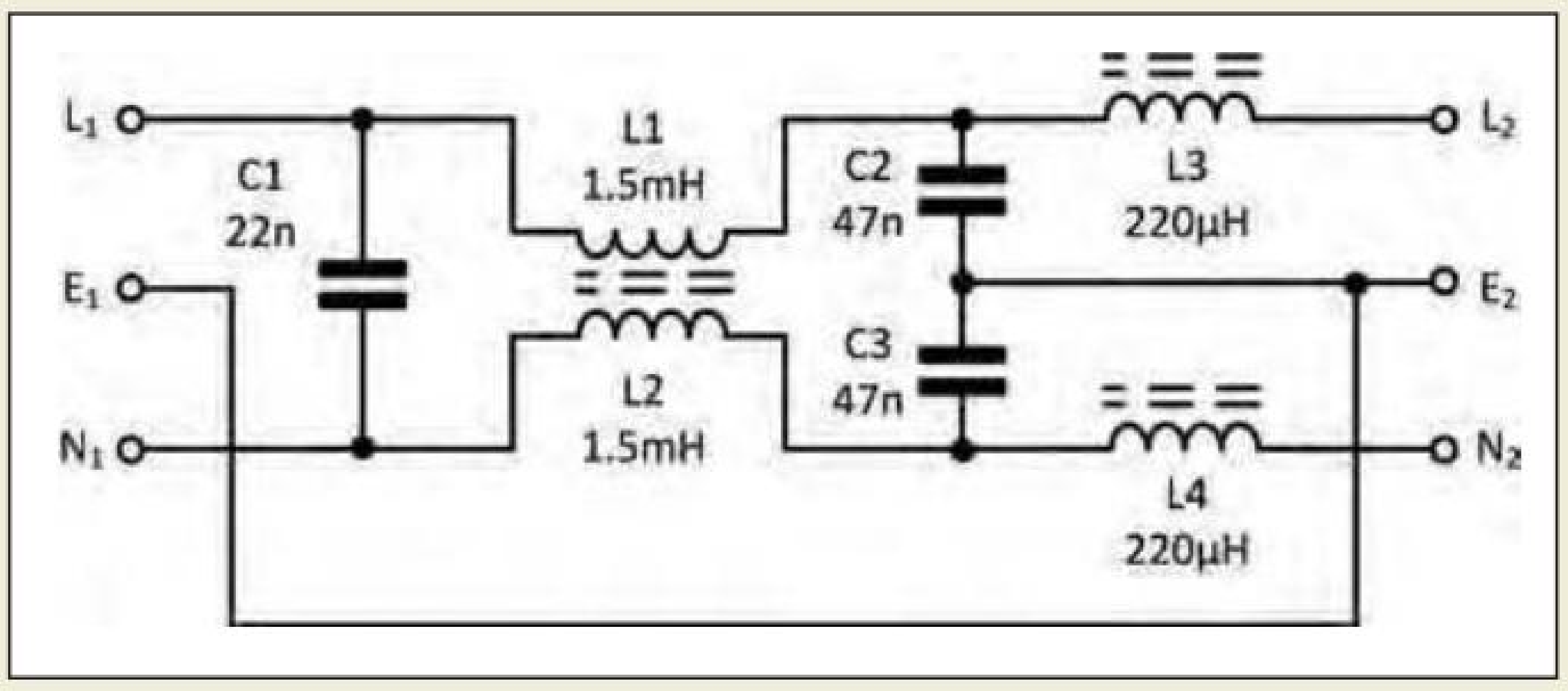

L₁
E₁
N₁
C1
22n
L1
1.5mH
L2
1.5mH
C2
47n
C3
47n
L3
220µH
L4
220µH
L₂
E₂
N₂

Fig.8.19. This typical SMPS EMI low-pass noise filter is designed to reduce conducted and radiated noise from mains wiring. L1 and L2 are wound on a small ferrite ring, while L3 and L4 are conventional axial components.

Inductive components are extensively used in EMI noise filters (see Figs.8.19 and 8.20) and in SMPS generally (see Fig.8.21). Fixed inductors are available in the standard series of E6 and E12 values but, in order to meet a particular set of requirements (notably value, current rating and DC resistance) you may need to manufacture your own inductors. Fortunately, this is not as difficult as it sounds. All you need is a suitably rated ferrite ring and a length of enameled copper wire of appropriate gauge.

Ferrite rings are available in several different grades with differing magnetic properties and covering different frequency ranges. The N30 grade is suitable for most general-purpose applications over a frequency range that extends from 10kHz to 400kHz and is thus ideal for use in most SMPS designs. Ferrite rings are also available in various sizes (see Fig.8.22). The three low-cost ferrite rings shown in Fig.8.22 are all manufactured from the same N30 grade ferrite but, due to the differences in dimensions, they exhibit different values of *specific inductance* (A_L) which determines the number of turns (n) that need to be wound on the ring in order to achieve a particular value of inductance (L) using the relationship:

$$n = \sqrt{\frac{L}{A_L}}$$

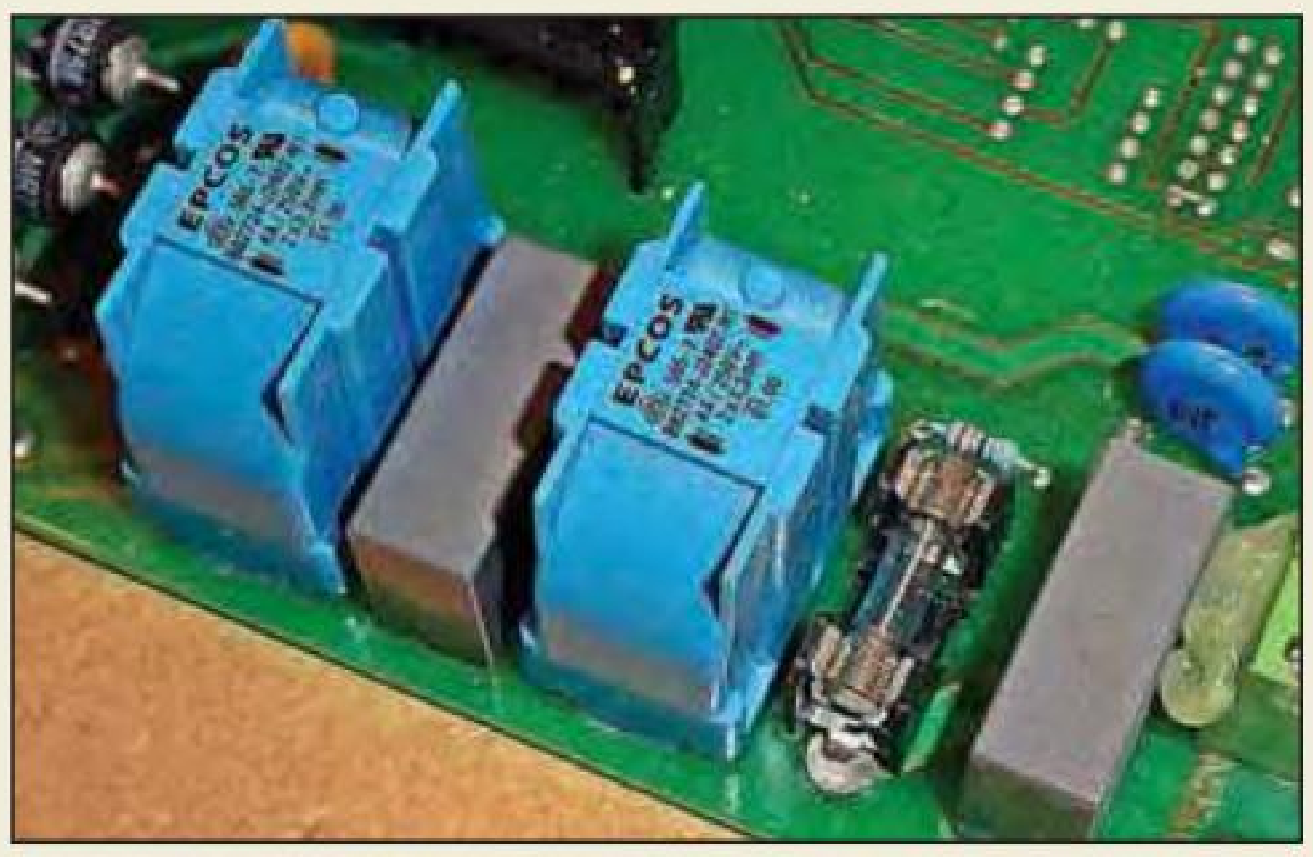


Fig.8.20. A mains filter using two encapsulated ferrite rings together with suitably rated capacitors. These certified Class-X or Class-Y components are designed specifically for use in AC line filtering and EMI/RFI suppression.

For example, if you require an inductance value of 1.5mH from the middle-sized N30 grade ferrite ring ($A_L = 4620$) shown in Fig.8.20 you can use:

$$n = \sqrt{\frac{1.5\times10^{-3}}{4620\times10^{-9}}} = \sqrt{325} = 18 \text{ turns}$$

Ferrite rings in various grades and sizes are available from several suppliers including Mouser, Farnell and RS Components.

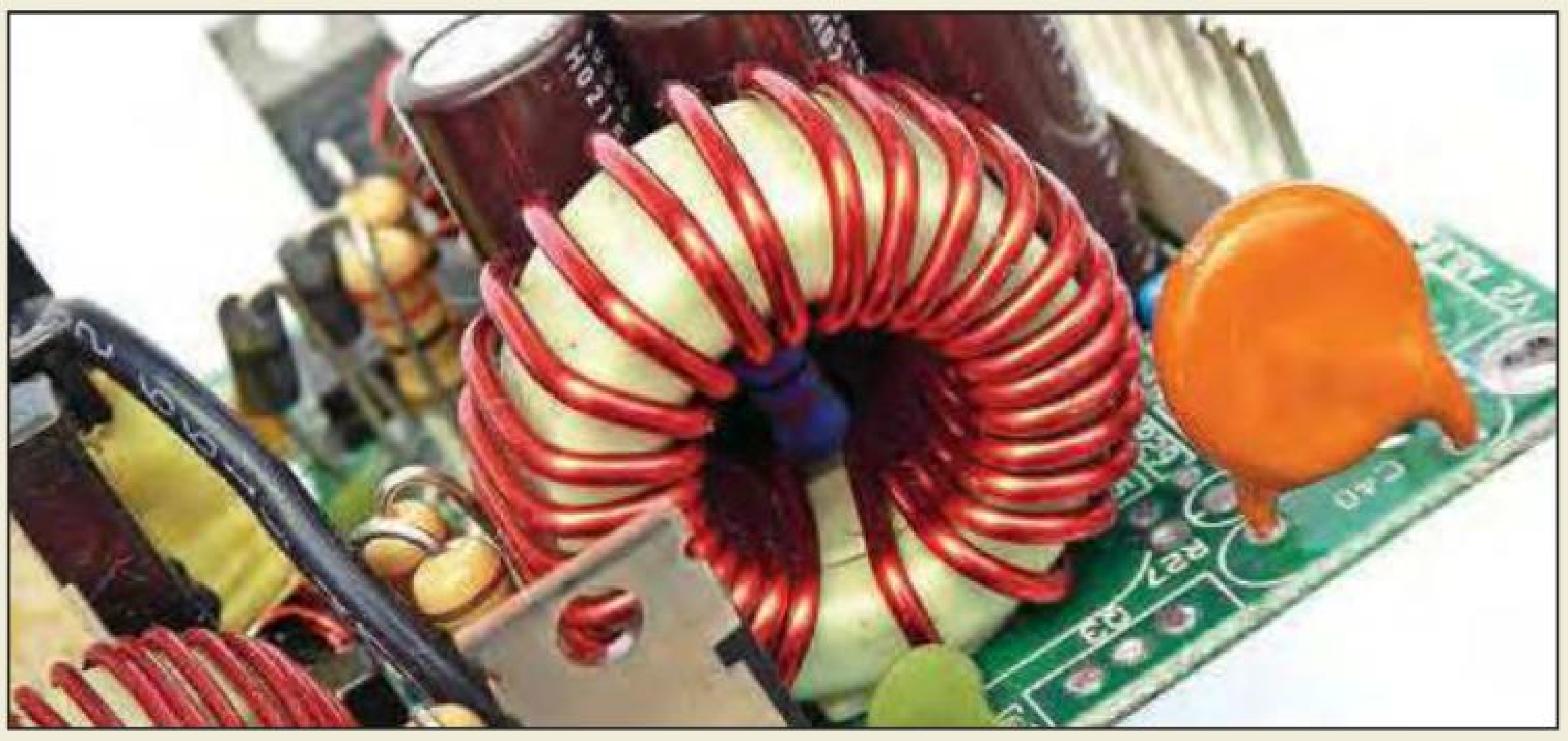


Fig.8.21. A typical SMPS inductor which can be easily manufactured using an off-the-shelf ferrite ring and a length of enamelled copper wire of appropriate gauge (see page 49 of April 2019 PE).

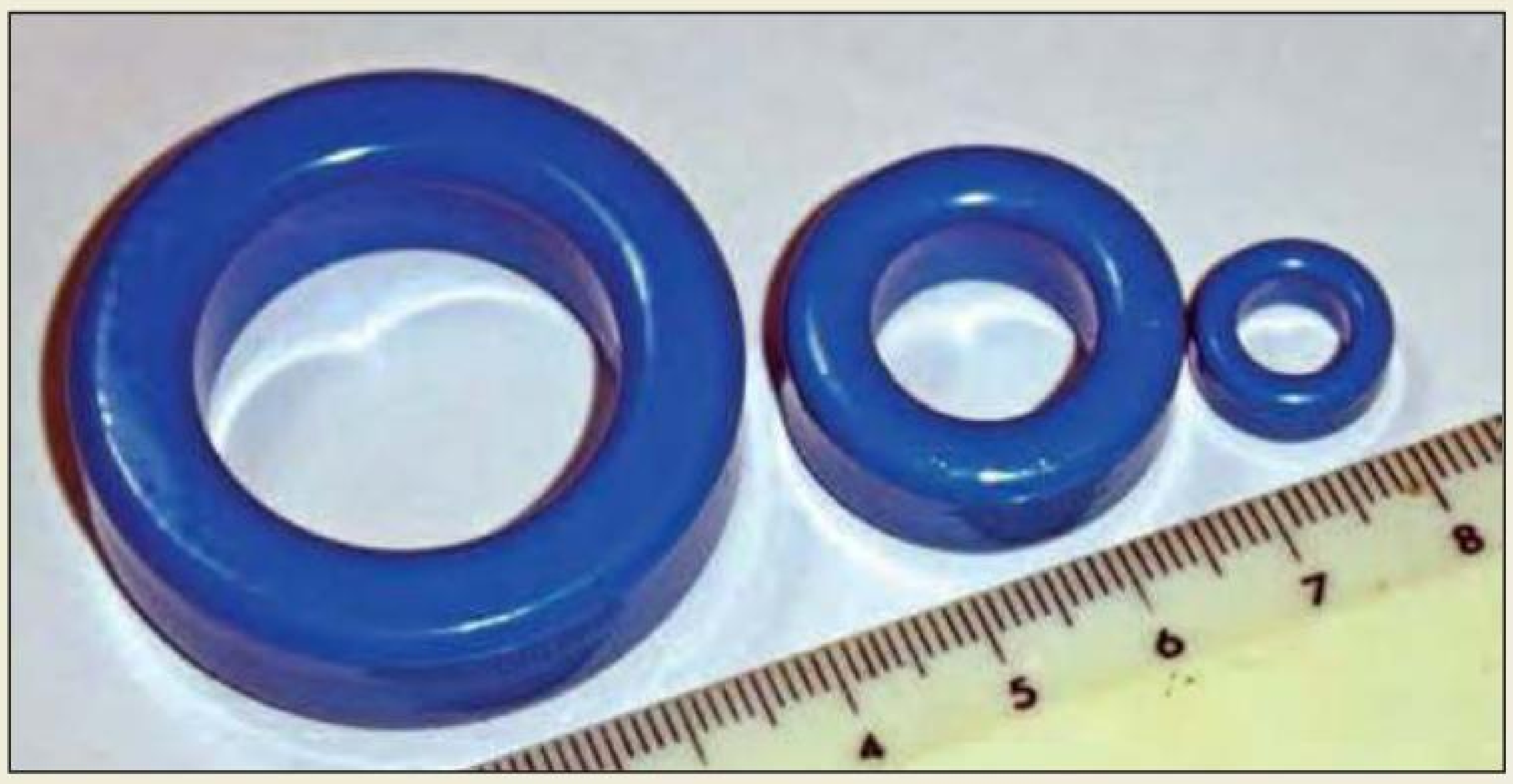


Fig.8.22. Low-cost N30 ferrite rings are ideal for construction of inductors for use in switched-mode power supplies (SMPS). These three rings have specific inductances of 2200nH, 4620nH and 5460nH.

Index – Teach-In 2019 Powering Electronics

A
AWG 5.49
Airflow 7.51
Ambient temperature 7.47
American wire gauge 5.49
Arduino 1.42

B
Battery 4.44, 4.47, 8.88. 8.46
Boost converter 4.42, 4.43, 4.46, 4.47
Booster regulator 3.47
Bridge rectifier 2.42, 6.45, 7.46
Buck converter 4.42, 4.43

C
Cables 5.49
Capacitor 6.47, 6.50
Capacitor failure 6.48
Charge pump 7.46
Chassis connector 3.50
Criticality 1.43
Current boosted regulator 3.47
Current limiting 3.47

D
DA 6.47
DF 6.47, 6.49
Derating 7.47
Dielectric 6.46
Dielectric absorption 6.47
Dissipation factor 6.47, 6.49
Duty cycle 1.43

E
ESL 6.47
ESR 6.46, 6.47, 6.48, 6.50
Earth connection 3.50
Effective series inductance 6.46
Effective series resistance 6.46
Efficiency 1.43
Electrolytic capacitor 6.46, 6.50
Energy density 6.47
Environment 1.43
Equipment fuse 4.48
Equipment wire 5.47, 5.49
Equivalent circuit 6.47
Equivalent series inductance 6.47
Equivalent series resistance 6.46

F
Fixed-voltage regulator 3.45, 3.46
Full-wave rectifier 2.41, 2.42
Full-wave voltage doubler 6.44
Fuse rating 4.48
Fuses 4.48

H
Half-wave rectifier 2.40
Half-wave voltage doubler 6.44
Heat shrink sleeving 3.50
Heatsink 7.47, 7.48, 7.49, 7.51
Hum 1.43

I
IEC connector 3.50
IEC mains plug 3.50
IR 6.47
Insulating washer 7.51
Insulation resistance 6.47
Inverter 7.47

J
Junction temperature 7.47

L
Leakage current 6.48
Line regulation 1.44, 5.45, 5.48
Linear power supply 1.42, 2.38
Linear voltage regulator 3.44
Load 1.43
Load regulation 1.43, 3.44, 5.45, 5.46
5.48, 6.50

M
MTTF 1.43
Mains connector 3.50
Mains fuse 3.50
Maintainability 1.43
Maximum total power 7.47
Maximum working voltage 6.46
Multiplier 6.44

N
N-tupler 6.45
Negative supply 7.46, 7.47, 7.49, 7.50
Noise 1.43, 1.44, 1.45

O
Output resistance 1.44

P
PWM 4.43
Peak load 1.43
Power transformer 2.39
Primary winding 2.40
Protection 1.43
Pulse-width modulation 4.43

Q
Q 6.47
Quadrupler 6.44
Quality factor 6.47
Quick-blow fuse 4.48

R
Rectifiers 2.40
Regulation 1.43
Regulation curves 1.44
Reliability 1.43
Reservoir capacitor 2.42,6.45,6.47,6.50
Reservoir capacitors 2.41
Ripple 1.44, 1.45, 2.41
Ripple current 6.47
Ripple factor 1.45

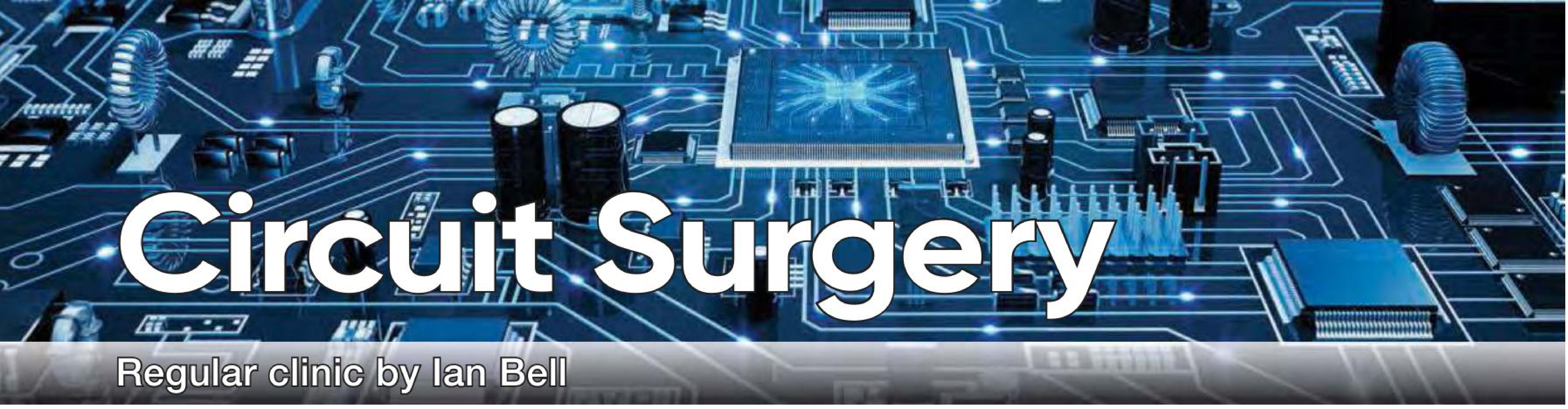
S
SMPS 1.42,4.42,4.43,4.44,4.45,4.46,5.44
SMPS controller 5.44, 5.45
SMPS principle 4.42
SMPS regulator 5.47
SMPS terminology 4.42
SMPS wiring layout 5.46
SWG 5.49
Safety 2.42
Secondary SMPS 4.44
Secondary winding 2.40
Shunt regulator 3.44
Slow-blow fuse 4.48
Standard wire gauge 5.49
Step-down converter 4.42, 4.43
Step-up converter 4.42, 4.43
Switched mode supply 1.42
Switching transients 1.45

T
TPV 2.39
Temperature 7.47
Temperature effects 6.48
Test load 1.44, 1.45
Thermal equivalent 7.49
Thermal resistance 7.47, 7.48, 7.51
Three-terminal regulator 3.45, 3.46, 7.47
Total power dissipation 7.47
Transformer 2.38, 2.39
Transistor mounting 7.48,7.51
Tripler 6.44
Turns per volt 2.39

V
VA rating 2.39
Variable test load 1.45
Voltage doubler 6.44
Voltage inverter 7.47
Voltage multiplier 6.44, 6.45
Voltage quadrupler 6.44
Voltage regulation 3.44
Voltage tripler 6.44
Volumetric efficiency 6.47

W
Windings 2.40
Wiring 5.49
Working voltage 6.48

Z
Zener diode 3.44



Circuit Surgery

Regular clinic by Ian Bell

Understanding bipolar junction transistors – Part 1

This month we will start to look at bipolar transistor configurations – common-emitter, common-base and common-collector. These are three ways to use transistors in circuits; and amplifiers and other designs are based on these architectures.

Recently, a question on the EEWeb forum simply asked what a particular circuit was, without giving a reason for an interest in it. The posted schematic looked like a textbook example, or an exercise for students. The discussion that followed pointed out that the circuit contained three transistors in different configurations. Unfortunately, it seems that the user who asked this question also posted numerous other questions, somewhat randomly – as Max Maxfield said, giving the 'impression that you are just pulling our legs with your queries'.

Despite this, the topic of transistor configurations is an important one and something that has come up before on EEWeb. For example, in a much earlier post, Vaishnavi Ramalingam asks why the common-emitter configuration is preferred. As was pointed out by Olin Lathrop in response, 'preferred' is not really the right term here. The choice of transistor configuration is based on its suitability for the task the circuit has to perform. The common-emitter configuration is suited to basic voltage amplifiers and is therefore very commonly used, perhaps giving the impression that it is preferred. Common-emitter circuits are probably those which most people are familiar with, followed by the common-collector variety and last, common-base.

To appreciate the differences between the different configurations it's useful to first look at some of the basics of transistor operation, transistor characteristics and the way transistors are modelled to facilitate circuit design, analysis and simulation. Although these ideas are used for detailed mathematical analysis of circuits, and can potentially get complex, they can also provide some insights without having to plough through pages of mathematical analysis.

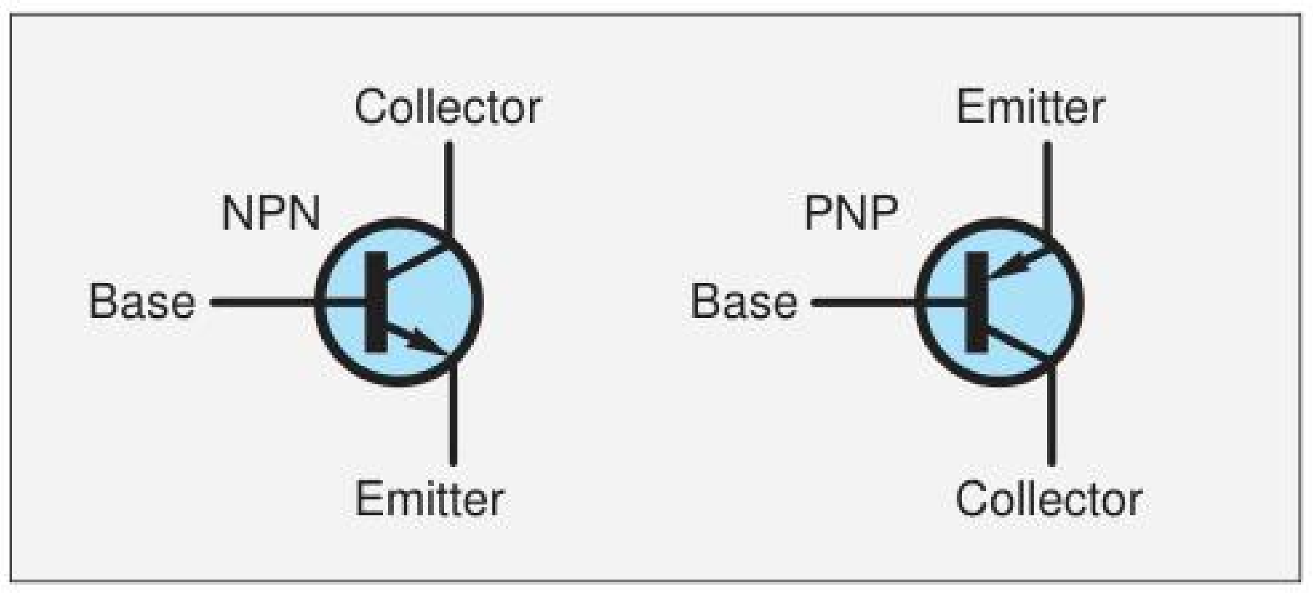


Fig.1. NPN and PNP bipolar transistors.

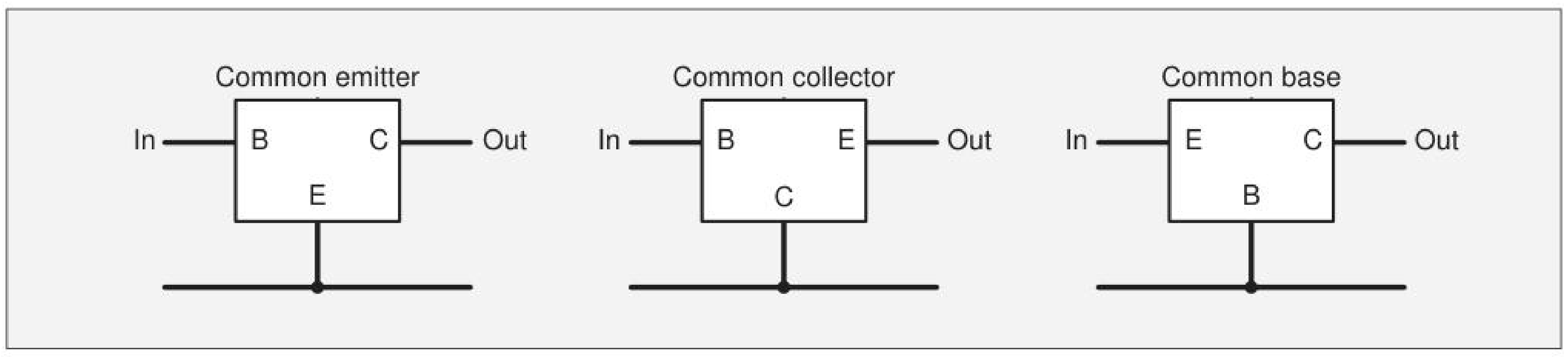


Fig.2. The three fundamental transistor configurations – these apply to both NPN and PNP devices. (Actual circuits require additional components.)

This month we will look at some basics of bipolar transistors, or 'bipolar junction transistors' (BJTs) to give them their full name, with some reference to the configurations. Next month, we will look in more detail at some example circuits in different configurations.

Transistor basics

As many readers will know, the bipolar transistor is available in two fundamental types: NPN and PNP (see Fig.1). These names refer to the structure of the semiconductor materials that form the device; for example, an N-type collector and emitter, and a P-type base in an NPN transistor (the base is the middle part of the arrangement). The junction between P and N material forms a diode, which only conducts in one direction. If the transistor was simply two diodes there would be little conduction between collector and emitter as there is an NP followed by a PN junction on this path. However, the base is very thin and this influences the physics of the device. As a result, a small base-to-emitter current is able to control a much larger current between collector and emitter.

The basic concept of transistor configurations is illustrated in Fig.2. Here we see an abstract representation of the transistor configurations as amplifiers with an input (to base or emitter), an output (from collector or emitter), and a common or reference connection (nominally ground or earth). It is the common connection (which can be any of the three terminals) that gives the configuration its name. No signal polarities are shown in Fig.2 and the circuits apply to both NPN and PNP. However, for the circuits to be actually implemented we need some additional circuitry to link the transistor (and load) to a power source and set up the correct operating conditions for the transistor (known as 'biasing').

Inputs and outputs

The inputs of the circuits in Fig.2 may be considered to be either voltages or currents – which of these is the most convenient or relevant may depend on the application or context of what we are trying to do. The output from a bipolar transistor is fundamentally a current, but this is readily converted to a voltage, if required, by passing it through a resistor. With both input and output taken as currents, we think of the transistor as a current amplifier, in which case the value of gain is a simply a number without units.

The best-known (current) gain associated with a transistor is the ratio between collector current and base current (symbol β), with the rule of thumb that the collector current is about 100 times the base current. This relates directly to the common-emitter configuration, which has the base as input and collector as output. For the common-base configuration the input-output

Simulation files

The LTSpice files discussed in *Circuit Surgery* are available for download from the *PE* website.

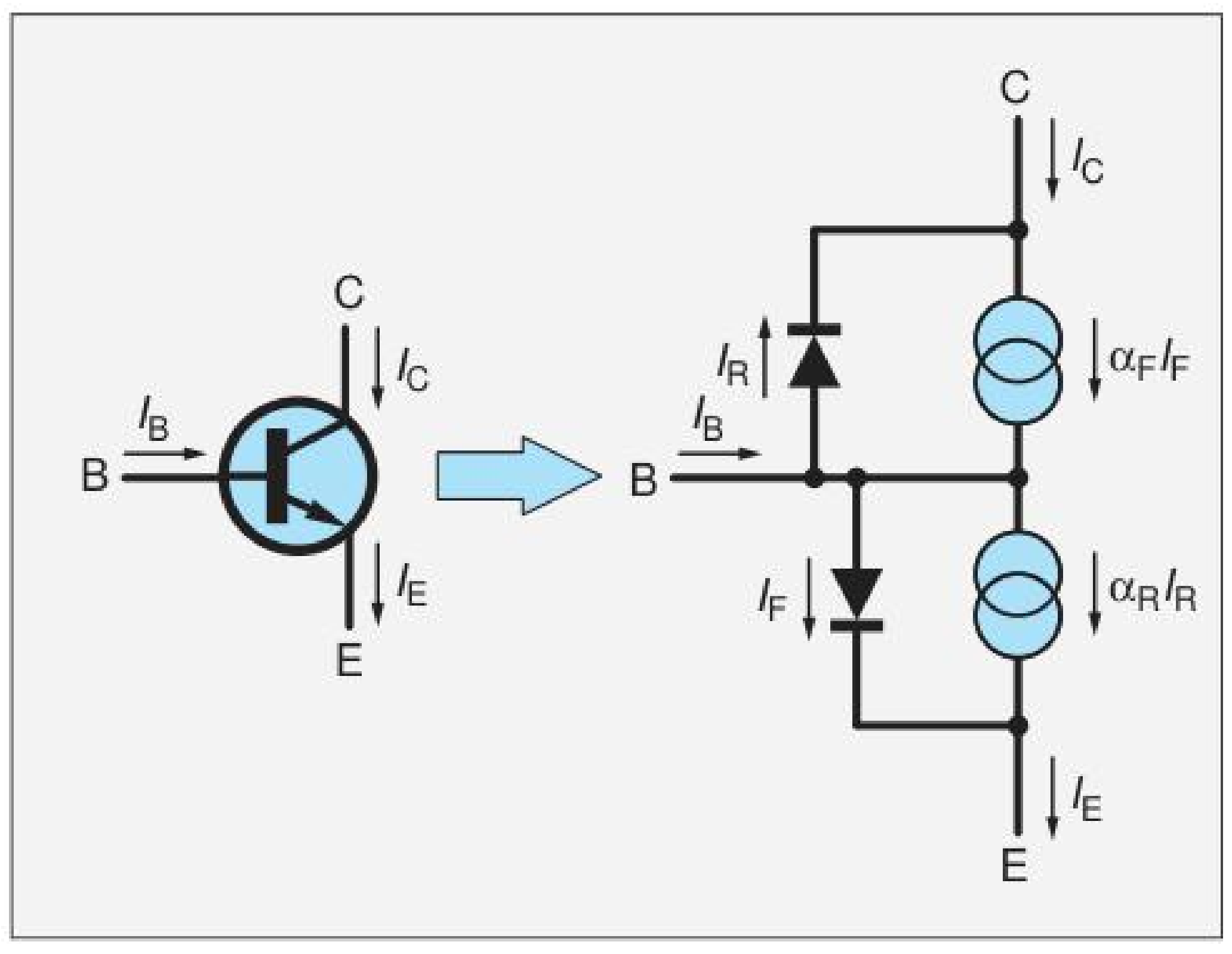


Fig.3. The complete version of the classic Ebers-Moll transistor model. (Simplified interpretations are often used.)

relationship is between the emitter and collector. These two currents are typically very similar, so the current gain for a common-base circuit is close to unity. This illustrates that the properties of the different configurations are different. You may think common-emitter sounds better because the current gain is higher, but this just one of the many properties that might be considered when deciding which configuration to use. Other important properties include input and output impedance and bandwidth.

Transconductance

If we consider the input to be a voltage rather than a current then the gain (output/input) is of the form current/voltage (output signal current amplitude divided by input signal voltage amplitude). We know from Ohm's law that voltage/current is resistance. The reciprocal of resistance is conductance, so a gain of the form current/voltage is a form of conductance – we call it 'mutual conductance', or 'transconductance', as an input-output relationship is involved. Its symbol is g_m. For a base-emitter voltage input, to collector current output, typical g_m values are from tens to low hundreds of millisiemens (mS). We get this range because transistor transconductance varies with collector current, as do many transistor parameters. This brings us to biasing – setting the basic operating currents and voltages of the transistor, around which point any signal variations occur.

It is well known that bipolar transistors require a certain amount of base-emitter voltage to be applied before they switch on and can operate as amplifiers. Setting this up is the basic requirement of biasing, but it is not the whole story – we can choose from a wide range of possible transistor operating currents with no signal present (zero input signal current or voltage). The choice will influence transistor parameters (such as gain) and also the characteristics of the circuit as a whole (for example, power consumption). Transistor data sheets often present graphs showing how various parameters vary with collector current and the approximate value of some parameters can be found using straightforward formulae. For example, the transconductance of a transistor is determined from the collector current (I_C) using $g_m = I_C/V_T$, where V_T is the thermal voltage, which commonly occurs in semiconductor equations. V_T depends on physical constants (the charge on an electron and Boltzmann's constant) and temperature. It has a value of about 25mV at room temperature (20°C).

Ebers-Moll model

Last month, we discussed modelling op amps for SPICE simulation, and likewise we often use equivalent circuits to represent the behaviour of complex devices. A widely used model of the bipolar transistor is shown in Fig.3. This is called the 'Ebers-Moll model' after Jewell James Ebers and John Louis Moll who published it in 1954. Here we see two diodes which relate to the PN junctions just discussed. There are also two current sources, whose currents depend on the diode currents – for example, the current from the collector source, $\alpha_F I_F$, depends on the current in the base-emitter diode I_F. This circuit looks complex, and its full form has some quite complex equations that go with it, but we can simplify things a bit.

Active modes

In a typical amplifier, a transistor's base-emitter diode is forward biased (conducting), but the base-collector junction is reverse biased (not conducting). When a transistor is operating in this way it is said to be in 'forward active mode' (hence the F subscripts in Fig.4). Fig.4 looks symmetrical, so we could reverse this situation (base-collector junction conducting, base-emitter off), which is called 'reverse active mode' (R subscripts). Transistors are not fabricated symmetrically, so the forward active mode is by design the one that gives optimal amplifier performance, and reverse active is rarely used. If both junctions are conducting the transistor is said to be saturated – this mainly occurs in in switching circuits. If neither junction is conducting the transistor is off, again this is used in switching applications. Our discussion here concerns amplifier circuits, so we will generally just be dealing with forward active mode.

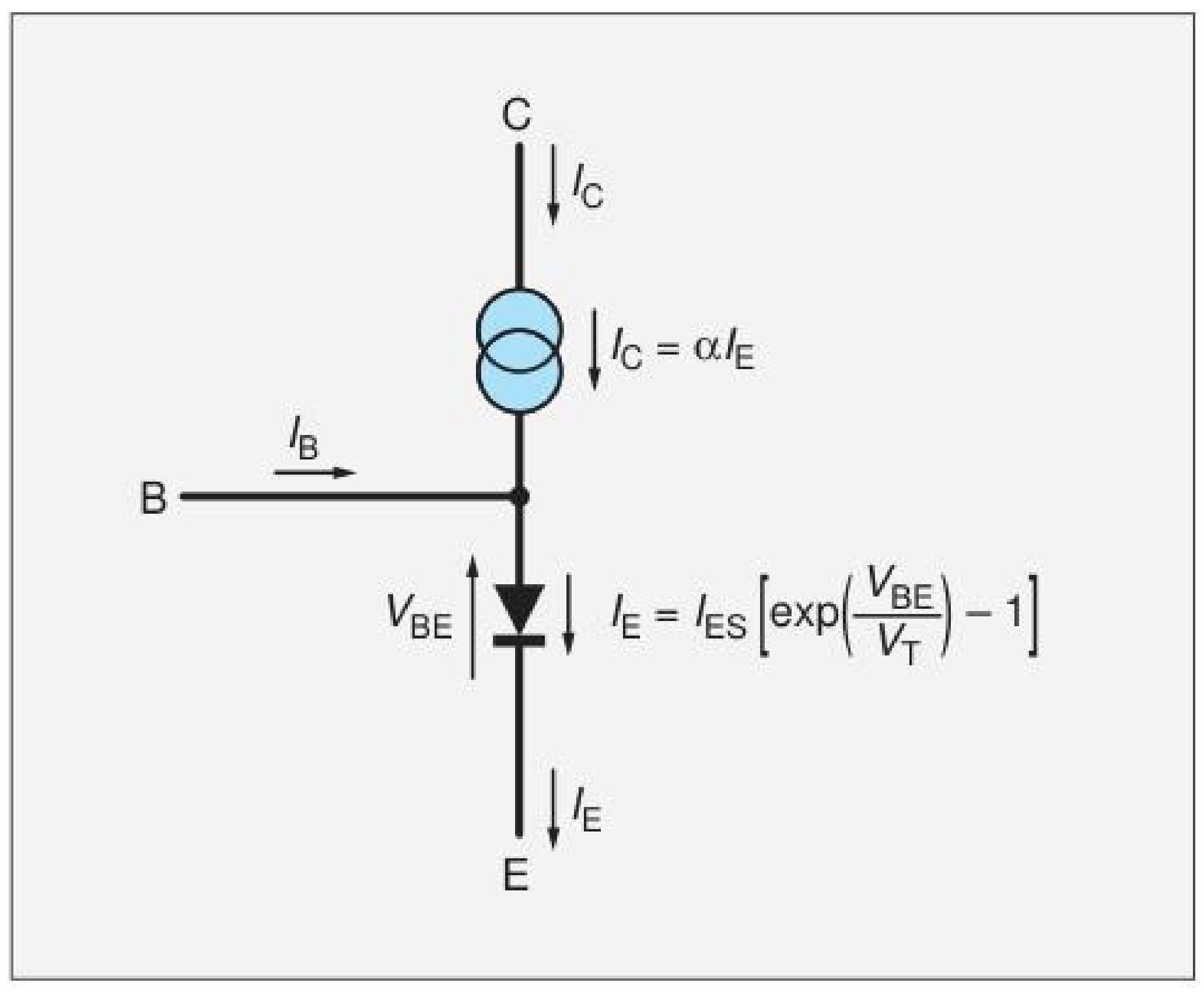

C
I_C
$I_C = \alpha I_E$
I_B
B
V_{BE}
$I_E = I_{ES}\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right]$
I_E
E

Fig.4. Simplified transistor model for forward active operation.

In the forward active mode I_R is close to zero and therefore so too is current source $\alpha_R I_R$. Hence the 'reverse' diode and current source have little effect and we can simplify the circuit in Fig.3 by removing them, leading to the circuit in Fig.4. Here we see the base-emitter as a forward-biased diode and the collector current is αI_E – that is, α times the diode current (α is typically about 0.99). To complete the picture we need to know the diode current. We can find this from the voltage across the diode (the base-emitter voltage, V_{BE}) using its characteristic equation – the relationship between the voltage across the diode to the current through it (I_E in this case), specifically:

$$I_E = I_{ES}\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right]$$

Here, V_T is the already mentioned thermal voltage. I_{ES} is the diode (or base-emitter junction) saturation current – a parameter specific to the particular diode or transistor.

Putting typical values into the above equation will give you the well-known requirement that the base-emitter voltage needs to be around 0.6V to 0.7V for the transistor to be conducting at typical collector current bias levels (say in the mA range) and have the ability to handle signals at typical levels for normal applications.

You may be wondering why the transistor model in Fig.4 does not include what is perhaps the best-known transistor parameter, the previously mentioned current gain β. The answer is that α and β are closely related, so we can use either. From Fig.4 we see that:

$$I_E = I_C + I_B$$

This is Kirchhoff's current law, and we also know:

$$I_C = \alpha I_E$$

Therefore:

$$I_C/\alpha = I_C + I_B$$

From this, and with a bit of algebra we end up with:

$$I_C = \alpha I_B/(1 - \alpha)$$

But we also know:

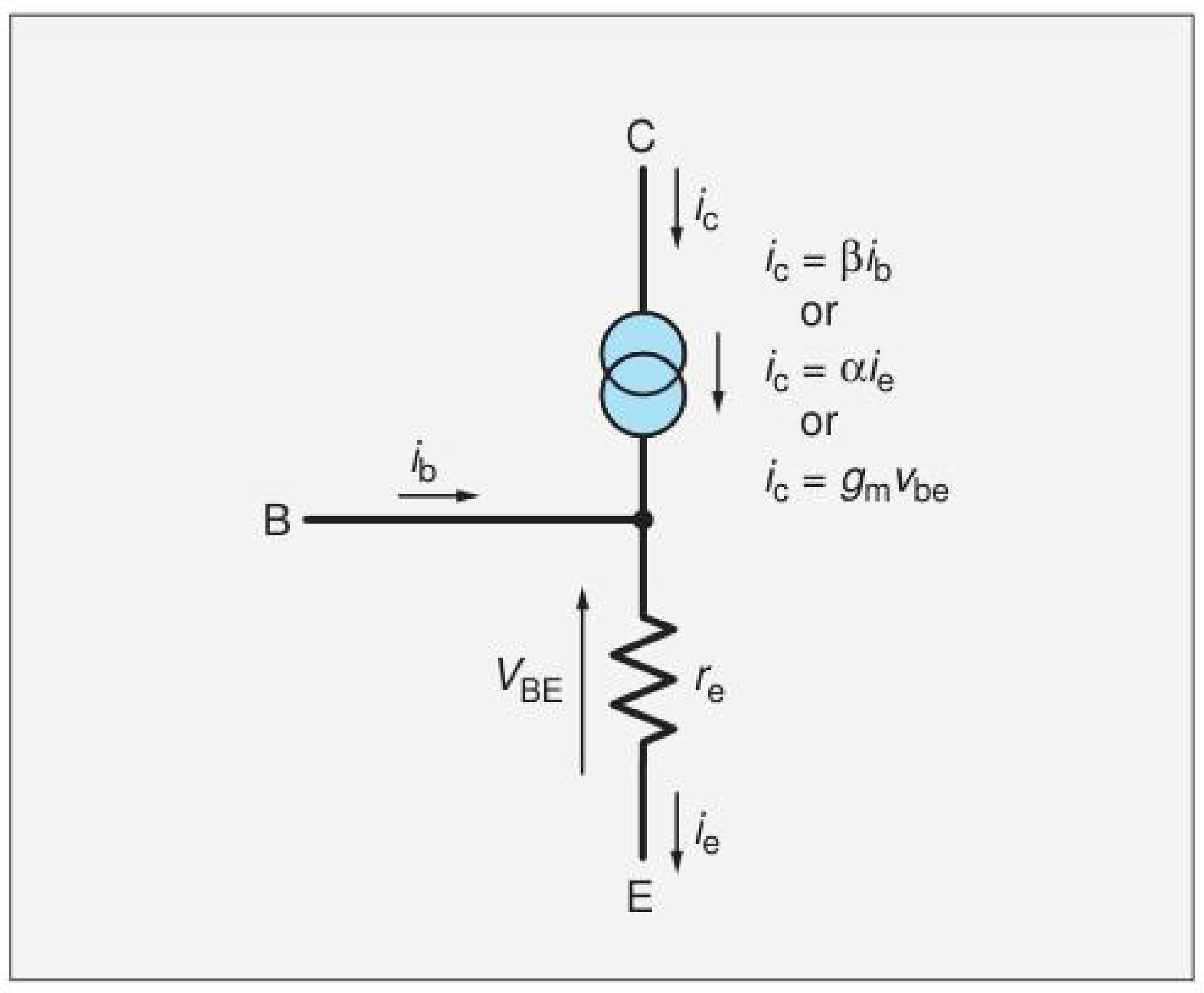


Fig.5. Small-signal (linearised) transistor model based on Fig.4.

$$I_C = \beta I_B$$

So $\beta = \alpha/(1 - \alpha)$. For a typical α of 0.99 we get $\beta = 0.99/(1 - 0.99) = 99$, agreeing with the rule-of-thumb β value of 100.

More advanced transistor models

We can reformat models like those in Fig.3 and Fig.4 to use different parameters. More generally, there are various forms of transistor models and variants of the different forms which use different sets of parameters. Conversion between different parameters may be straightforward – as with α and β just discussed – but there is certainly potential for confusion. We discussed simplifying the Ebers-Moll model – simple is good for hand calculations and understanding basic circuit operation, but of course in other situations high accuracy is required, for example in the models used in simulators. The Ebers-Moll model does not cover everything, in particular the fact that the value of β varies with transistor current. This is covered by the more comprehensive Gummel–Poon model and its variants (there are always variants), which is widely used in SPICE type simulators. (The Gummel–Poon model was published by HK Gummel and HC Poon in 1970.)

Small-signal transistor models

The various models discussed above are all what are called DC or 'large-signal' models. They cover the entire range of possible currents and voltages in a transistor. However, their complexity and the non-linear equations on which they are based make them difficult to use for some calculations and simulations. The alternative is an AC or 'small-signal' model. These only deal with signal variations, not the totality of the current and voltage in the circuit. Large-signal models are applicable to setting up bias conditions and operating points. Small-signal models are used to analyse signal-related properties, such as amplifier gain, input and output impedance and frequency response.

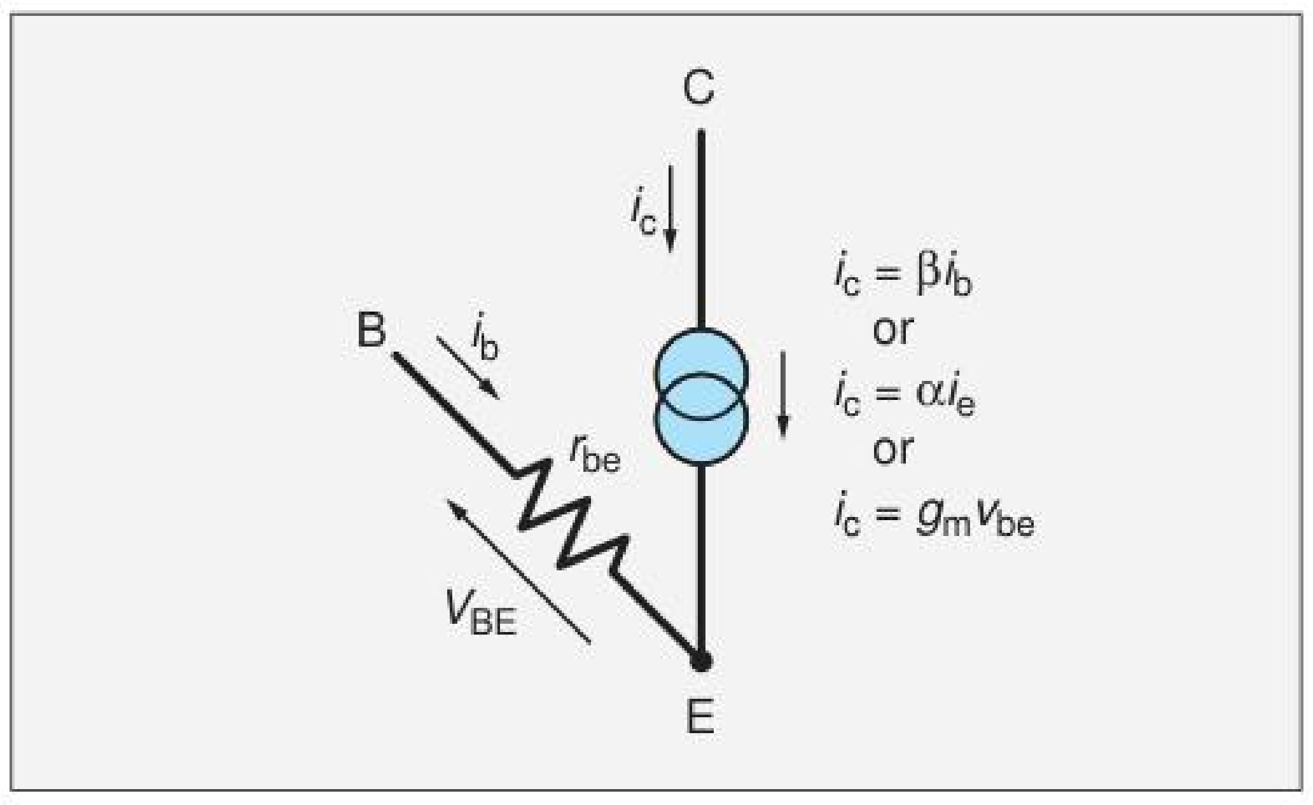


Fig.6. Transistor small-signal model with r_{be} instead of r_e.

Dynamic emitter resistance

Once the operating point is set we can consider a signal (the signal we are amplifying) which only causes a small variation in collector current around the operating point. For example, a variation of a few millamps, or less, rather than the range of microamps to hundreds of milliamps, or wider, that could be encompassed by the transistor at various operating points. Under this restriction the relationship between base-emitter voltage and current is approximately linear. To put this another way, over its full range the current-voltage relationship is an exponential curve, but if we just consider a small range, then that part of the curve can be approximated to a straight line. A straight-line current-voltage relationship is that of a resistor – so the diode in Fig.4 can be simplified to a resistor (the emitter resistance r_e) if we just consider the signal variations. Based on this, a small-signal version of Fig.4 is shown in Fig.5. Here, r_e is sometimes called the 'dynamic emitter resistance' to highlight the fact that its value changes with the transistor's bias conditions. At room temperature r_e is approximately $25/I_E$, with I_E in milliamps (mA).

Small-signal analysis

We can express the signal current in the collector (i_c) using α, β or g_m. The specific values of these gains will depend on the DC collector current I_C, as discussed earlier. Note the convention of using upper-case symbols for DC (bias) values and lower-case symbols for AC (signals). The small-signal values refer only to the signal variation. For example, if the collector current was biased to 10mA and varied from 9.9 to 10.1mA with a signal present, i_c would be 0.1mA (peak) and I_C would be 10mA.

The circuit in Fig.5 can be rearranged to a different form – different model structures facilitate analysis of different types of circuit. By Ohm's law the value of v_{be} is given by:

$$v_{be} = i_e r_e$$

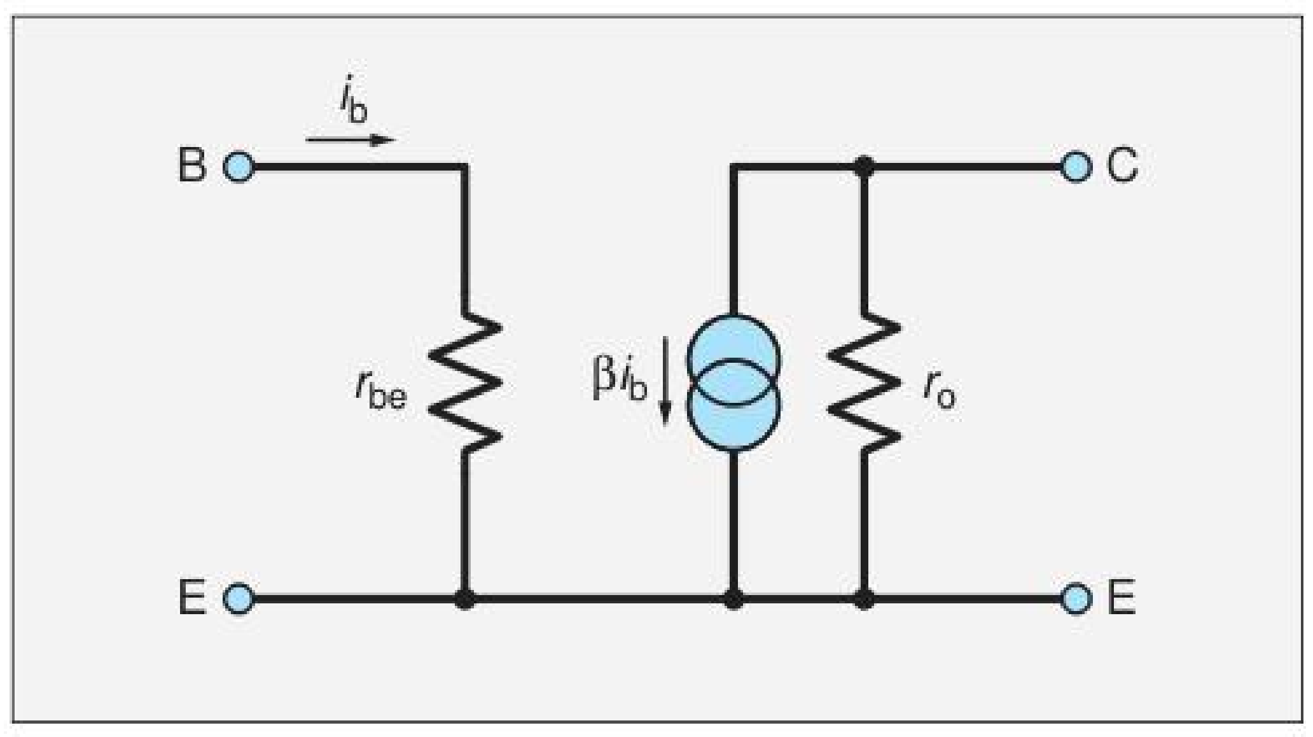


Fig.7. Fig.6 redrawn to a more convenient layout with output resistance (r_o) added.

But from but Kirchhoff's current law:

$$i_e = i_c + i_b$$

And we already know that:

$$i_c = \beta i_b$$

Therefore:

$$i_e = \beta i_b + i_b = (1 + \beta) i_b.$$

Substituting this in the v_{be} equation we get:

$$v_{be} = (1 + \beta) i_b r_e$$

We can consider just the base current flowing through a resistor (call it r_{be}) between base and emitter, then from Ohm's law we have:

$$v_{be} = r_{be} i_b$$

Comparing this with the previous equation for v_{be} we get:

$$r_{be} = (1 + \beta) r_e$$

Thus we can change the model circuit to that in Fig.6.

Transistor small-signal models are commonly drawn with the layout shown in Fig.7, but with many variations in the components included. Fig.7 shows the current source with $i_c = \beta i_b$, but the g_m form can also be used. The models in Fig.5 and Fig.6 imply that the transistor can act as an ideal current source, which is not the case in reality. To address this, an output resistor (r_o) can be added, as shown in Fig.7. The hybrid-pi and *h*-parameter models are well known small-signal models for transistors that take the general form shown in Fig.7. We only added r_o, but other components can be added to the model to take account of characteristics which are of interest. For example, capacitors can be added to model the high-frequency behaviour of transistors if we are interested in analysing a circuit's high-frequency behaviour.

Next month, we will look at some actual amplifier circuits. The models discussed so far may seem somewhat abstract at this point, but they can be used to help understand the characteristics of practical circuits.

AUDIO OUT

By Jake Rothman

The PE Theremin – Part 2

In Part 1 of the new PE Theremin project we introduced the basics of Theremin design and operation. This month, in *Part 2*, we will discuss our first board and device selection.

Transistor options

Component selection is of course important for all designs, but Theremins are particularly sensitive in this respect, so I will provide some in-depth advice. Let's start with transistors.

Standard high-gain low-frequency transistors, such as the BC549C, may give rise to 'squegging' (an undesirable low-frequency 'farting' noise) when used as theremin oscillators. A better choice is to use an RF transistor with a low H_{fe} of around 50, such as the BF199, BF495, BF195, KSP10TA, or KSC1674YBU. These also give smoother tuning, especially the types with variable gain used in intermediate frequency (IF) amplifiers with AGC (automatic gain control) in AM radios.

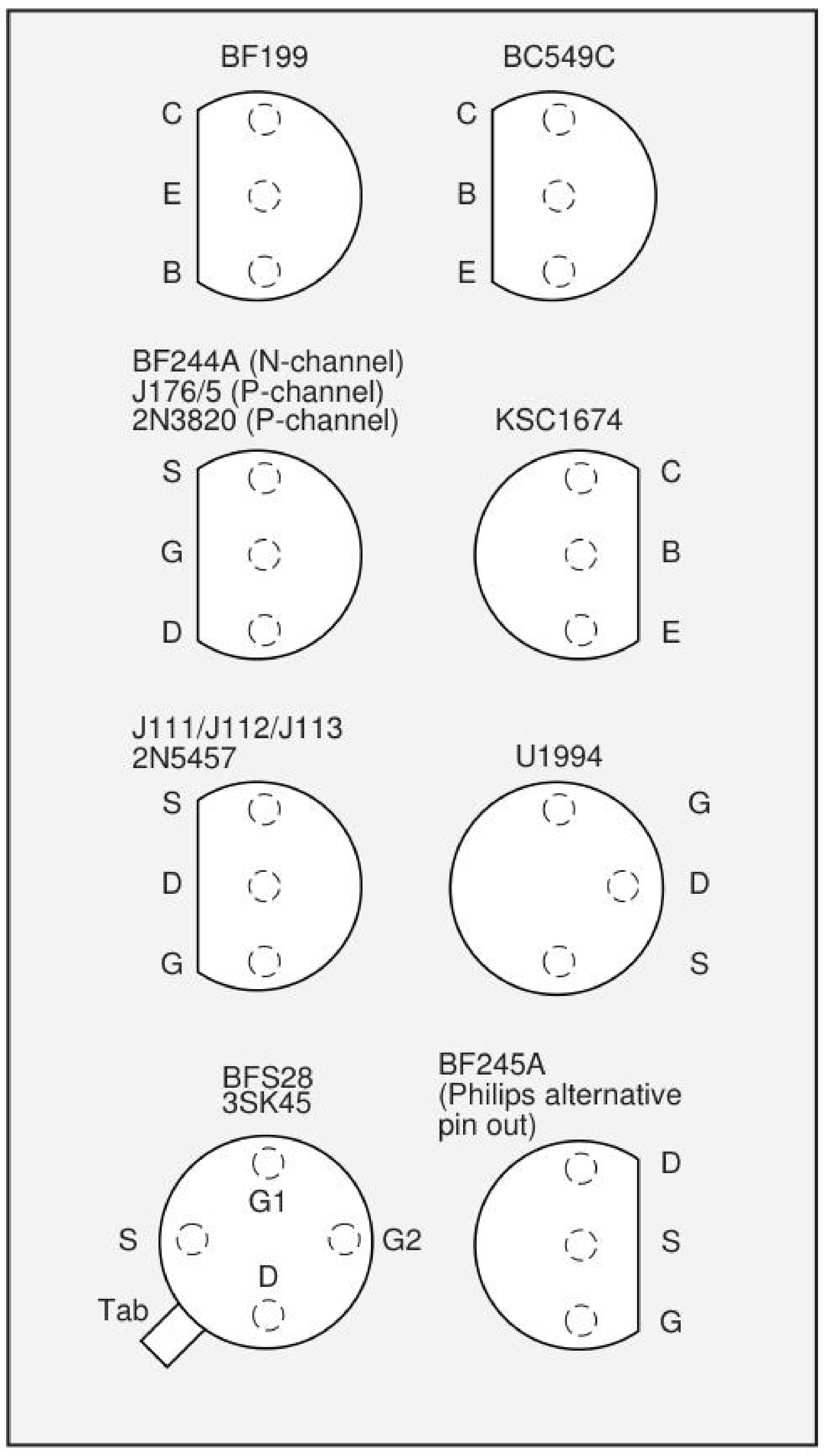


Fig.15. Top view of pin outs of semiconductors used for the *PE Theremin* pitch board.

These transistors are becoming hard to get. The BF199 has now been discontinued, but I managed to buy a load from Farnell a few years ago. They are still available from Technobots (**www.technobotsonline.com**) and many eBay sources. Mouser have big stocks of the KSC1674. Note that the PCB (see Fig.19) caters for different oscillator transistor pin outs. For example, the BFxxx series and KSP10TA are peculiar in having a centre emitter. The other transistor position on the board is for standard centre-base pin-out devices, such as the BC182B. The key point is you only need to use TR1 and TR2, or TR5 and TR6, not both pairs – *do see the notes about transistor options in the Pitch board parts list.*) Note also that the KSC1674 is centre-base, but the collector and emitter are transposed, so if you are using this device for TR1 and TR2 then remember that the 'D' shape on the PCB silk screen needs to be 'rotated' by 180°.

A handy aspect of this design is that the oscillators, apart from the aerial, are basically the same and tend to drift (thermally) together.

For the FET buffers, almost any N-channel device will work, such as the BF244A, 2N5458, or J113. The board pin-out is for centre-gate devices. Since JFETs are symmetrical with regards to their source and drain, these two pins can be flipped with no problem. It's as well to check the output with a 'scope if an 'odd' FET is used. If it is clipped, the 3.9kΩ source resistor will have to be tweaked. Through-hole JFETs are also becoming difficult to get. I noticed Mouser had massive stocks of J113s and J176s, so I bought a 1000 for less than 12p each to be safe. (I also bought the last of the Tayda BF244s – but eBay is always your friend here!). The pin-out details of all the suggested devices are shown in Fig.15.

Critical capacitors

The only critical capacitors are the padder (C5 and C11) and the feedback (C6, C7 and C12, C13) ones used in the oscillators. It is not the tolerance that is critical, since this is trimmed out and dominated by the inductors, which can be ±10%. It is their temperature drift that is most important. These capacitors should be zero temperature coefficient (NP0/C0G) ceramic, or mildly negative-temperature coefficient types, such as, –330ppm/°C ceramic, polystyrene or polypropylene capacitors. The inductors and metal antennae have a positive temperature coefficient, which can be cancelled out, to some extent. I use the TDK NP0 ceramics from Mouser for the relatively high value 10nF (C12 and C13) capacitors.

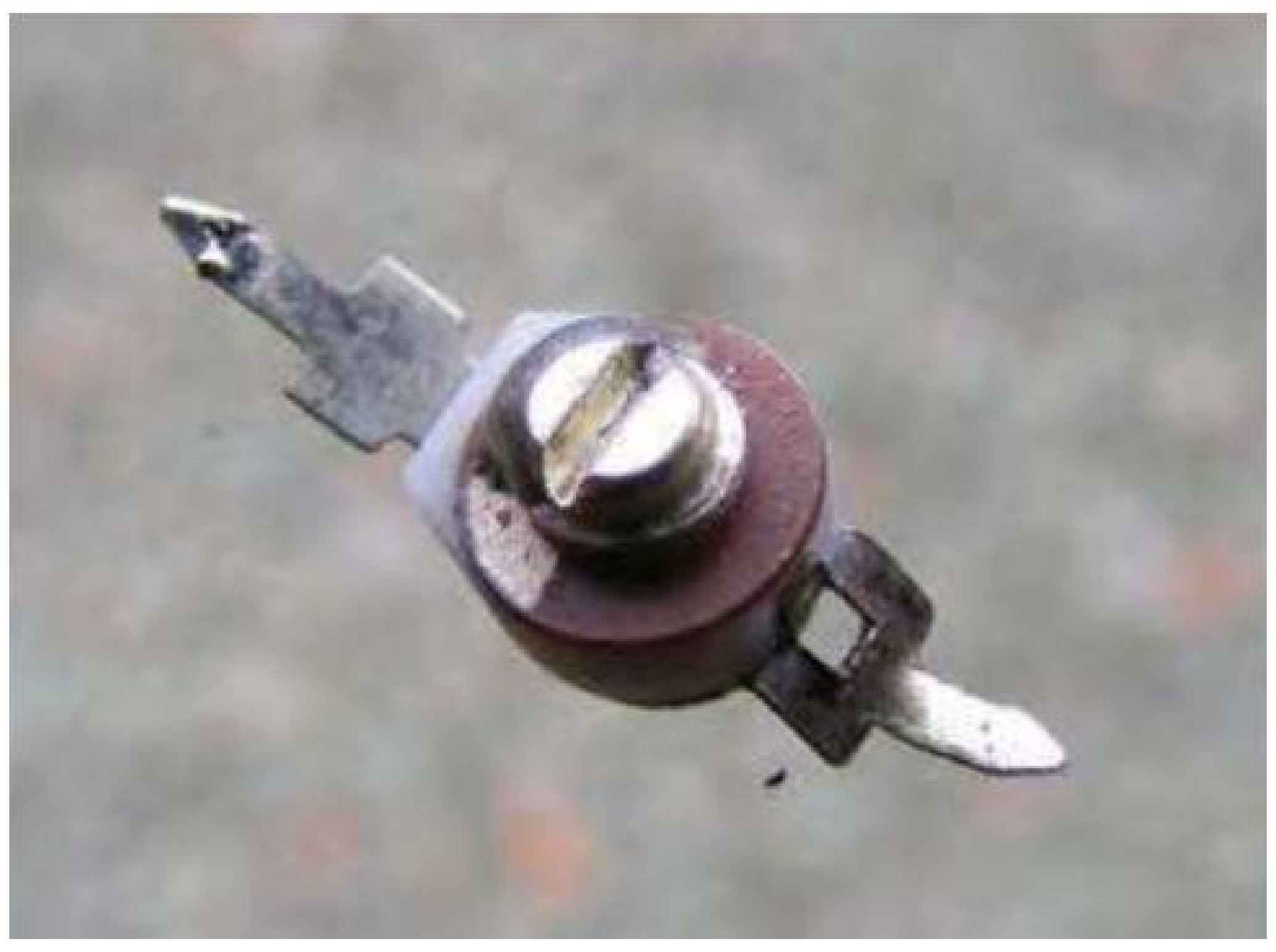


Fig.16. Cheap ceramic trimmers such as this Murata one are not very stable in Theremin circuits.

The oscillator decoupling capacitors C2 and C8 need to have low ESR (equivalent series resistance), so solid aluminium polymer types, such as those by Nichicon, Wurth and the Panasonic Oscon series, are the most effective. Tantalum types generally have too high ESR, unless specially designed, and wet aluminium electrolytics won't be effective at high frequencies. Interestingly, these capacitors and C10 need to be a much bigger value than the high frequencies would suggest, typically 10µF, because of the low beat frequencies that Theremins generate.

The trimmer capacitors are very important in this design. Cheap ceramic ones, such as the one shown in Fig.16 tend to be unstable. The older Mullard, Philips, BC components plastic-film types, which are shown in Fig.17 are

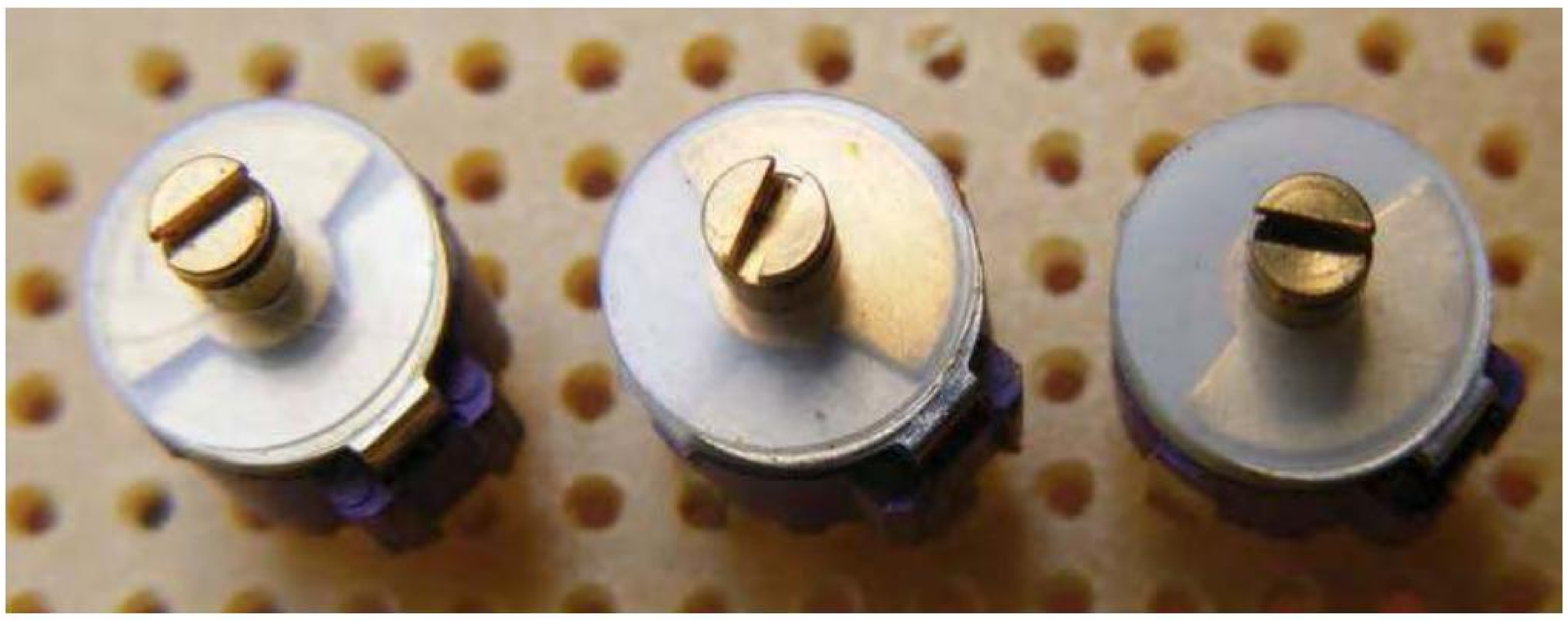


Fig.17. Plastic-film trimmers offer adequate stability and it's easy to see the positions of the plates. From left to right, minimum capacitance, half capacitance and full capacitance.

much better. Unfortunately, they are now only made by Vishay who are cornering the passive component market with an aggressive acquisitions policy and price increases. Even at Mouser, they now cost a few pounds each. Luckily, John Birkett's have a good stock at around 30p and I have bought a few thousand to ensure supply. Eventually, I may have to move to trimmer inductors, such as Xicon IF transformers, but with the decline of AM radio these are going to be difficult to get as well. (I'm used to these supply problems in analogue audio, since I am often asked to repair or modify studio equipment with a typical lifetime of 30 years or more. However, when the price of a component goes up, a cheap Chinese copy soon appears, such as blue 'Bourns' style trimmer resistors.

Mortal coils

Surprisingly, inductors are much less of a problem than they used to be. I used to design them out of circuits. Tayda and Mouser have a full range of values, just like resistors. I have used the TDK, Bourns, Taiyo Yuden and Sigma types with good results. As a general rule of thumb, the lower the parasitic capacitance and the higher the self-resonant frequency the better. This aspect is most critical for the loading inductors (L1, L2) in the pitch board and L2 in the volume board. The series resistance can be relatively high, so there's no need to buy expensive switched-mode power supply inductors.

Tuning the Theremin

Transparent plastic-film trimmer capacitors give a clear indication of the position of the moving plates. Fig.17 shows (from left to right) the trimmer at maximum capacitance with the plates fully enmeshed, then half-way and finally minimum capacitance. It is ideal if the trimmer is half way-when tuned, because there is then some leeway for adjustment in both directions. If the trimmer is too far over one way, the associated padder capacitor will have to be adjusted. Note that these capacitors have an 'earthy' side, which is the moving plates connected to the brass screw. The stator plates are 'live' (the middle protruding pin), which should go to the sensitive part of the circuit. This makes adjustment easier with a metal screwdriver. (Interestingly, the US symbol for capacitors makes this distinction, with the curved plate being earth.)

The coils and capacitors are 5% tolerance, which means a worst-case difference of 20% between the oscillators, not including any other factors. At 1MHz the audio could be way out by 200kHz. At **Theremin.co.uk** we avoid this by always using inductors from adjacent positions on the production roll. If you want to test the Theremin boards without aerials, temporarily soldering 22pF caps across the trimmer caps enables them to be tuned in. Remember, when checking the oscillators with a 'scope to set the probe to ×10 to minimise its capacitance. The voltage can be quite high, often higher than the supply voltage, a characteristic of inductor-loaded circuits.

Pitch board parts list

I produce many Theremins, so I have stockpiled parts – I can supply all these weird parts at a sensible price via: **jacob.rothman@homecall.co.uk**

Don't get caught out by the 'antique-dealer' spivs on eBay. I use and recommend John Birkett's, a historic analogue shop who can supply parts including trimmer capacitors. In fact, they're so 'historic' and 'analogue' that they don't do email:

25 The Strait
Lincoln
LN2 1JF
Tel: 01522 520767

Resistors (*All 0.25W 5% carbon film*)
R1 820Ω for pitch board only or 430Ω for powering the VCA and volume boards for a complete Theremin in *Part 3*.
R2, R5 39kΩ
R3, R6 4.7kΩ
R4 560Ω
R7 2.7MΩ
R8 1MΩ
R9 2.7kΩ
R10, R19, R20 47kΩ
R11 6.8kΩ
R12 100kΩ
R13 68kΩ
R14, R15 2.2MΩ
R16 3.9kΩ
R17 100Ω
R18 470kΩ
R21, R22 82kΩ
R23 2.2kΩ
VR1 47kΩ potentiometer (linear)

Capacitors (*All 5mm lead pitch, all 10V or higher*)
C1 10µF electrolytic
C2, C8 10µF low-ESR polymer or tantalum, eg Nichicon RNU1A100MDS1 Mouser
C3, C9 10nF X7R ceramic
C4 120pF 5% NP0/C0G ceramic (*not on circuit diagram, but do use!*)
C5 33pF 5% NP0/C0G ceramic
C6, C12 100pF 5% NP0/C0G ceramic
C7, C13 10nF 5% NP0/C0G ceramic TDK FG28C0G1H103JNT6 from Mouser or Wima polypropylene/polystyrene
C11 82pF 5% NP0/C0G ceramic
C14, C16, C18, C19 1nF X7R ceramic
C10 1µF tantalum or Y5V ceramic
C15 2.2µF tantalum
C17 3-40pF plastic-film trimmer capacitor Vishay/Philips/Mullard BFC2 808 11409 violet body 7.5mm obsolete (available from author) or green top / grey body 10mm BFC2 808 31409 available from Birkett (cheap) or Mouser (very expensive).

Inductors
L1, L2 270µH Bourns 77F271J-TR-RC axial (Mouser) or TDK ferrite bead radial 5mm (author)
L3, L4 100µH Bourns 78F101J-RC Mouser or Taiyo Yuden LA L 03TB 101K

Semiconductors
TR1* and TR2* centre-base RF transistors, eg 2SC1674
****OR*** use TR6 and TR5 positions for BF199 centre-emitter devices.
TR3 BC549C audio high-gain NPN or similar
TR4 BF244A N-channel JFET or similar
D1 BZY88C6V2 6.2V Zener diode
D2 1N4148

Audio Out files

The PCB CAD files used in this article are available for free download from the *PE* website.

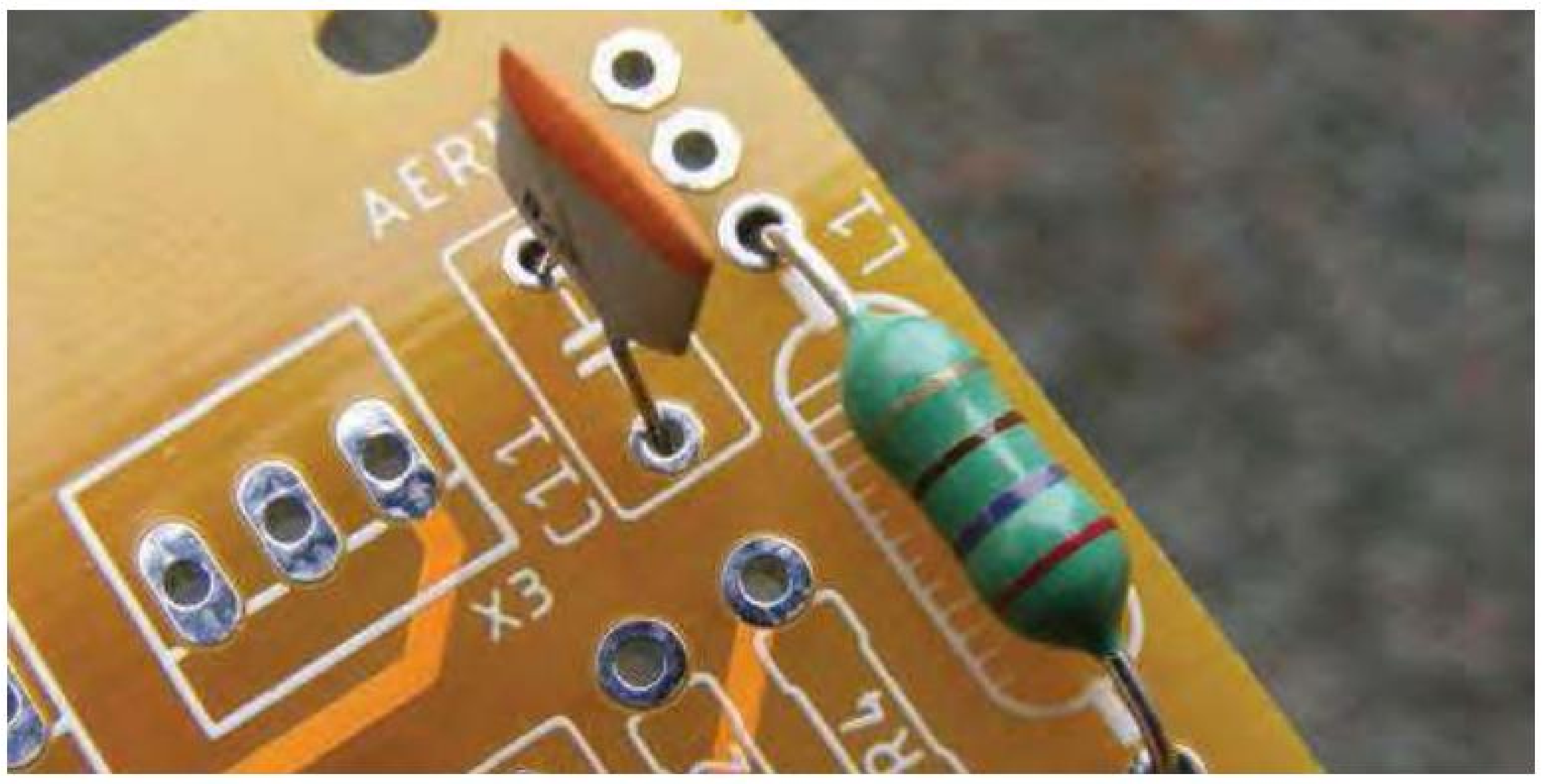

AERIAL
L1
X3
R1

Fig.18. Placing C11 next to the loading inductor caused locking which created a harsh sound, resulting in a PCB redesign.

Hardware

- PCB – the EagleCAD design is availabe for free download from the July 2019 issue's page on the *PE* website. A full set of PCBs will be available after the next issue is published.
- The aerials are made from 8mm gas restrictor tubes, from Screwfix, Part No. 48486, 3 lengths, £9.99

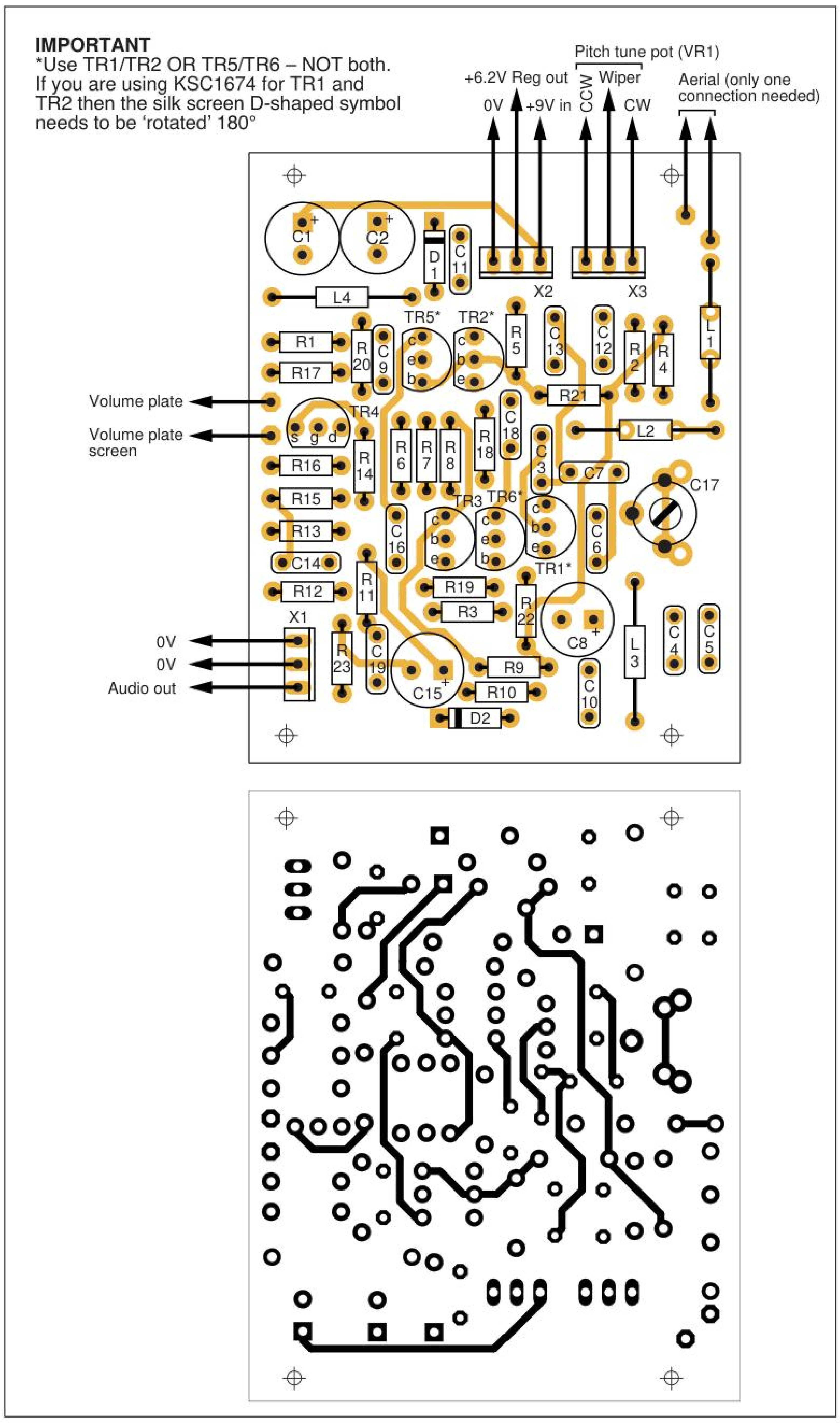

IMPORTANT
*Use TR1/TR2 OR TR5/TR6 – NOT both.
If you are using KSC1674 for TR1 and TR2 then the silk screen D-shaped symbol needs to be 'rotated' 180°
Pitch tune pot (VR1)
+6.2V Reg out
0V
+9V in
CCW
Wiper
CW
Aerial (only one connection needed)
Volume plate
Volume plate screen
0V
0V
Audio out
C1
C2
D1
C11
X2
X3
L4
TR5*
TR2*
R1
R17
R20
C9
R5
C13
C12
R2
R4
L1
R21
TR4
s g d
R16
R14
R6
R7
R8
R18
C18
C3
L2
C7
C17
R15
R13
C14
R12
C16
R11
TR3
TR6*
C6
TR1*
R19
R3
R22
C8
X1
R23
C19
C15
R9
R10
D2
C10
L3
C4
C5

Fig.19. Pitch board PCB layout – just the component-side tracks are shown. Note the dual outlines for the oscillator transistors. Positions TR5 and TR6 are for centre-emitter BF series transistors, and TR2 and TR1 are for centre-base top-collector types. See Fig.5 in *Part 1* for a photograph of this board.

- The die-cast ally box is from Hammond Mfg, Part 1550G, which costs about £18.00 from Mouser 546-1550G. There's a black one available for £20.00, Part 1550GBK. (Or use a wood or plastic case.)

Miscellaneous

3-pin 0.1-inch Molex connectors headers, housings and pins (4 off)
The trimming tool for the Theremin capacitors is a Bourns H-90, available from Mouser.

PCB layout considerations

If you design a circuit that can detect minute variations in capacitance then it follows that the PCB layout is critical. Normal RF design techniques apply; such as placing inductors as far apart as possible and at right angles to each other to minimise magnetic coupling – especially important here to minimise locking. Note how the two oscillator inductors are in opposite corners of the board. Also, circulating current loops, such as from the oscillator to its decoupling capacitor, have to be kept as short as possible. Placing a ground plane on the board to minimise electrostatic coupling helps. However, this has to be kept away from the aerial connectors, since the whole point is to detect capacitance to earth. In addition, there should be no conductor near the inductors since this will lower the Q – akin to a shorted turn on a transformer.

It's also essential to keep sensitive components apart. For example, on the pitch board, the aerial-loading inductor (L1) must not be placed near the fixed oscillator's padder capacitor, C11. I had to scrap the first edition of the pitch board because C11 was radiating into L1 (see Fig.18) causing premature locking. Simply moving C11 near its associated inductor (L4) fixed the problem. The pitch board layout is shown in Fig.19. Note that a DC-isolation capacitor has been inserted in the aerial connection. This is on the PCB, but not last month's circuit diagram (Fig.5).

Next month

In *Part 3* we'll look at capacitive volume controls and other system blocks to make a complete Theremin.

References

Integrated Circuits and Transistor Gadgets Construction Book by BB Babani, 1974 No. 203.

A summary of Theremin's life can be found in *Electronic Sound* magazine issue 21 by Robert Webb.

Albert Glinsky's Leon Theremin biography is recommended if you need more: *Theremin: Ether Music and Espionage*.

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PICn' Mix

Mike Hibbett's column for PIC project enlightenment and related topics

Small, cheap and powerful – Part 3

Over the last two months we have been experimenting with the PIC10F202, one of Microchip's tiniest microcontrollers. We developed a smart power on/off circuit, shown in Fig.1, as the first example design to explore. This month, we add the code to make it do something useful and start to show how its versatility can make it a more useful device than even the venerable NE555 timer chip.

Before we delve into software (and finding out whether the functionality we want will even fit in such a tiny chip,) let's talks about the chips themselves, and some of the challenges chip designers, and the people who create products based on those chips, have to deal with.

Challenges of small ICs

The world is awash with microprocessors and microcontrollers of ever growing complexity and capability.Nevertheless, there is still a need for tiny compute devices – providing the brain for smart bicycle lights that respond to sharp deceleration, or the Bluetooth trigger button on selfie sticks (yes, they do exist, sadly.) You might think that there is no limit to how few features chip manufacturers will offer, but in fact there are practical limits.

You can think of a silicon chip as a small multilayer PCB (it's not a bad analogy.) When chip manufacturers talk about, 'The latest 10nm technology processors', the 10nm dimension refers to the smallest feature that can be resolved – think of it as a track width/spacing size. While we might be happy with track dimensions of 0.2mm, the latest technology processors can have features down to 10nm – that's 0.00001mm! When the author was first working in an IC design group, the feature sizes were 3µm or 0.003mm – clearly, as the features get smaller, individual components get smaller, and so you can pack more on the same sliver of silicon – or use a smaller piece of silicon, to make the part cheaper. Although that is exactly what happens, and we can now have microcontrollers no smaller that a grain of rice, a feature that has not changed over the years is the size of the bond pad. The bond pad is the area on the silicon reserved for connecting a thin wire from the silicon to the external pins of the device. These features remain quite large, relatively speaking, so there will always be a limit to just how small you can make the piece of silicon because you always need bond pads. It's a complete waste to leave silicon unused, as it does not reduce the manufacturing costs, so features stay in.

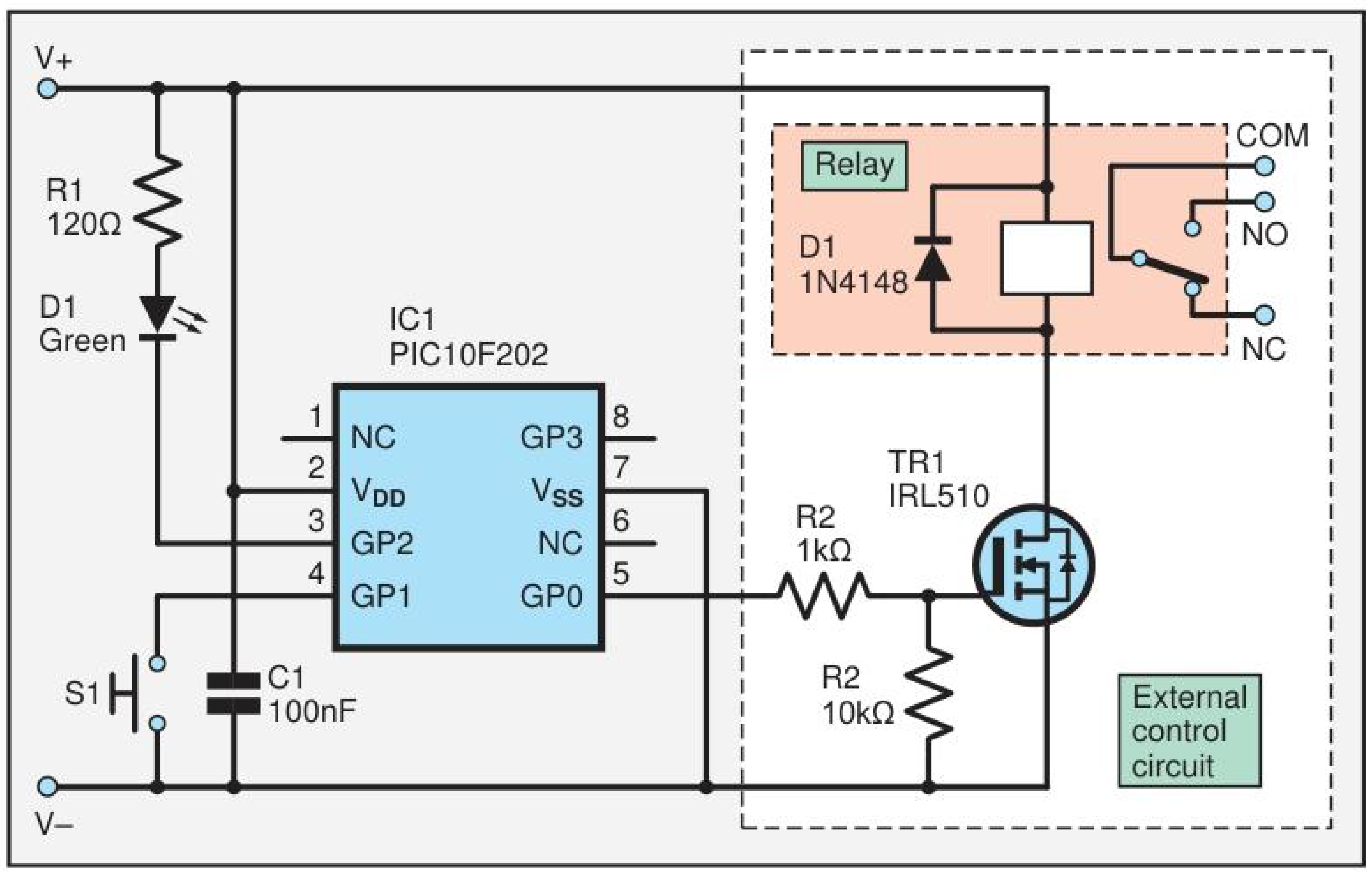

Fig.1. Smart switch circuit

PIC n' Mix files

The programming files discussed in this article are available for download from the *PE* website.

The other interesting factor is that with very small ICs the cost of the IC packaging can be more than the cost of the chip itself. Add to that the time spent testing and calibrating each chip and you realise that running an efficient manufacturing plant is vital to making any profit!

Back to software

Now let's dive into the software for our smart power on/off switch. As with most software projects it helps to start by writing down the requirements (what you want to do) followed by creating a design – a statement of how you expect the software to do the job. For a project like this, a simple flowchart should suffice to describe the design. Flowcharts may be a rather ancient design technique, but they are perfect for this kind of application; one that should follow a simple flow of execution, which is what we expect the design to look like once it is complete. Our requirements are:

1. Debounce the push switch, turn output on if button still pressed after debounce.
2. Turn the output off after a programmed delay (say, 30 minutes, or longer.)
3. If the output is on and the button is pressed again for a long period (say, 3 seconds) turn the output off immediately.
4. If the output is on and the button is pressed, flash the LED to indicate power is about to be turned off, if the button continues to be pressed.
5. Draw very low power when the switch is turned off (the circuit will run on batteries.)

Low-power operation

To achieve very low power consumption while actively monitoring the push switch, we will make use of the microcontroller's `SLEEP` instruction. This turns all the microcontroller's clocks off, bringing the current consumption down to less than 1µA. Reading through section 9.9 of the microcontroller datasheet (**http://bit.ly/pe-jul19-mc**) provides an explanation of how the `SLEEP` instruction works, and how a wake-up caused by a GPIO input change can be detected. The key point to note is that after running the `SLEEP` instruction the

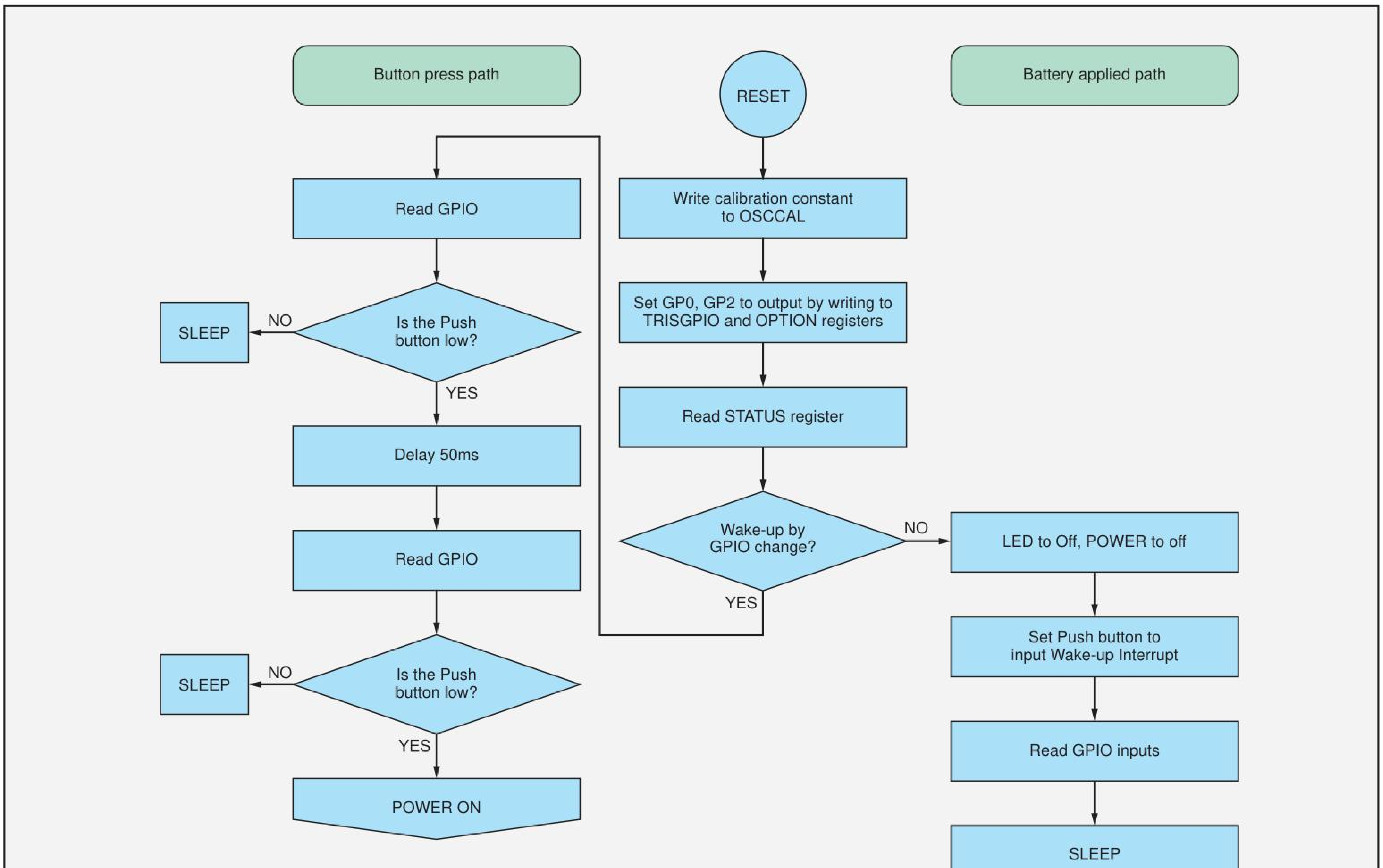

Fig.2. Start-up flowchart

microcontroller will halt, turn off its clocks and wait for a change on a GPIO input. When that change occurs, the microcontroller will perform a `RESET`, starting the program running from the beginning. So, handling the key-press event is something we must do at power up. This sounds a bit upside-down, but the technique is quite common – your application simply reads the `STATUS` register at start-up to determine the reason for the `RESET`, and branches to the appropriate code.

Section 9.3 describes how the different causes for a `RESET` can be determined. There are several reasons for a `RESET` condition to occur, all of which can be determined by reading the `STATUS` register:

- Power-on Reset (POR)
- MCLR Reset during normal operation
- MCLR Reset during Sleep
- WDT time-out Reset during normal operation
- WDT time-out Reset during Sleep
- Wake-up from Sleep on pin change
- Wake-up from Sleep on comparator change

We are only interested in two cases: 'Wake-up from Sleep on pin change', which we will take to be in response to a button press, and 'any other reason', which we will consider to be a normal power-on scenario. This is a reasonable approach because the MCLR (master clear reset), WDT (watchdog timer) and comparator features are not being used.

Armed with this information we can proceed to design the program. We will approach the design in bite-sized chunks, starting with a very high-level design. We will then isolate sections of the design that do not suggest an obvious implementation and expand on those sections by drawing flowcharts for just those sections. By taking this approach the design can be evolved into a detailed enough description of the application such that converting the design into actual code – be that in 'C' or in assembly language – becomes a simple step.

Evolving the design

Sometimes, as the design is evolved, you discover a roadblock; you find that your design can go no further without some ugly hacks or you simply cannot see how to progress. With experience these situations become rare, as you look at a set of requirements and think, 'This problem is like one I have solved before, where I used such-and-such design. I'll re-use that approach'. If you are unlucky and hit a roadblock you simply start over again from scratch but make use of the thought process from the first attempt and your increased knowledge of the problem to consider a better high-level design. Hopefully, that will not happen in this design – we shall see!

High-level design

From reading section 9.3 and 9.9 of the datasheet we know that on application start-up we have to look for why the application started and branch the code path right at the beginning of execution based on whether it was a power up or a key press. Let's draw this part of the design as a flowchart, to start us off. The diagram is shown in Fig.2.

Even for what should be a relatively simple block of code, the diagram is quite complex. This is just our start-up code. We haven't even got to the meat of the application yet! However, if you study the diagram in detail and read sections 9.3 and 9.9 of the datasheet, you will see that this flowchart can be easily translated directly into code – 'C', or assembly language for that matter. Each box shape will translate to a single instruction or two, and each diamond to two or three. We addressed many of these coding requirements in last month's article, so we can reuse much of that code. Let's go ahead now and translate this first flowchart into a real program.

One point that is interesting about this first flowchart is that it introduces no variables; there is one inside the 50ms delay routine that we reuse from last month, but this diagram, complicated though it is, introduces no new ones. It's going to be interesting to see just how much Flash memory that complex diagram takes up!

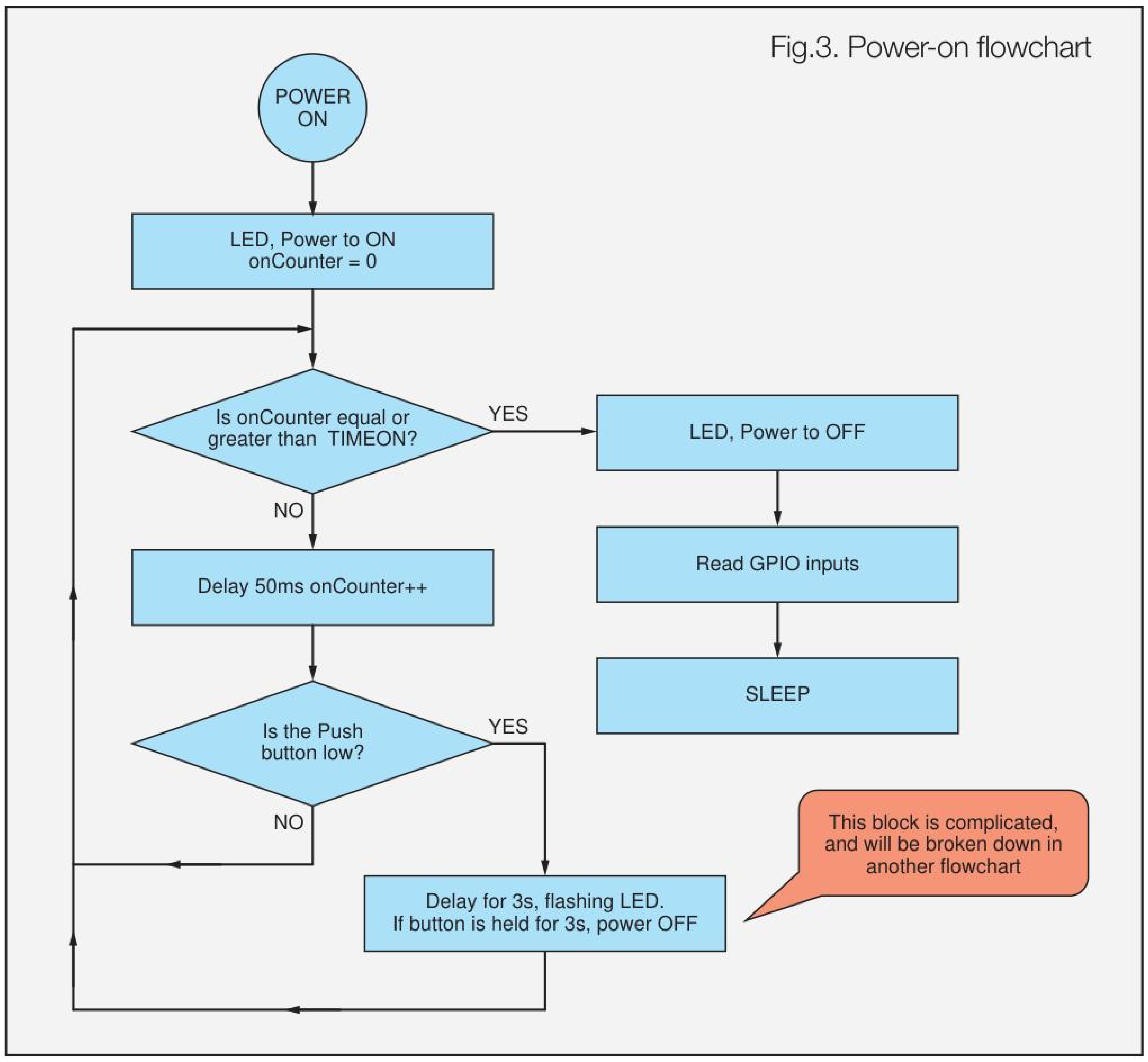
POWER ON
LED, Power to ON
onCounter = 0
Is onCounter equal or greater than TIMEON?
YES
NO
LED, Power to OFF
Read GPIO inputs
SLEEP
Delay 50ms onCounter++
Is the Push button low?
YES
NO
Delay for 3s, flashing LED.
If button is held for 3s, power OFF
This block is complicated, and will be broken down in another flowchart

Fig.3. Power-on flowchart

Listing 1: Source code for start-up

```
OPTION = 0x1F;
TRISGPIO = 0x02;

if (STATUSbits.GPWUF) {
    STATUS = 0;

    // Read GPIO
    pinStatus = GPIO;

    // IS the button low?
    if (pinStatus & 0x02) {
        // It is not low – so sleep
        asm(“SLEEP”);
    } else {
        delay_50ms(1);

        pinStatus = GPIO;

        // Is the push button low?
        if (pinStatus & 0x02) {
            // Not low – so sleep
            asm(“SLEEP”);
        } else {
            // POWER ON
        }
    }
} else {
    // A normal power-up condition
    // LED to OFF, Power to OFF
    GPIO = 0x04;

    pinStatus = GPIO;

    // Sleep
    asm(“SLEEP”);
}
```

The code for Fig.2 is shown in Listing 1. There is a ‘stub’ of code related to the ‘Power On’ functionality, which we will detail in the next flowchart. This code, coupled with the 50ms delay routine from last month, compiles to just 93 words of program memory and 9 bytes of data RAM. Last month’s code was 73 words of program memory and 8 bytes of data RAM, so that whole flowchart occupies just 20 words of program memory!

Fig.3 shows the flowchart for the main part of the application, handling the power on functionality. This progressed quite easily, until we came to the section relating to handling the detection of a key press to trigger a power off. That requires flashing an LED, timing 3 seconds count down, while still maintaining the 30-minute count down. Ah, that’s going to be tricky. So once again we leave a ‘stub’ for this, a block that simply says, ‘delay for 3s’. We will do a flowchart for that later. Listing 2 shows the code for this flowchart, with the stub again left as a simple comment.

At this stage the code is functional and useful, but it just does not provide the capability to turn the power off with a button press. That single requirement will turn out to be the most complex of all the requirements, and it will be interesting to see what impact that single requirement has on our project.

At this point our code space has grown by just 10 words to 103 words of Flash, and 11 bytes of data RAM. Those extra two bytes are due to the addition of a new variable, `onCounter`, which is of type unsigned short – a 16-bit variable. This will count the number of 50ms periods that has elapsed, and so with a maximum value of 65535, it can hold a delay time of up to 54 minutes. Using a larger variable to hold a longer delay would cause the code space to increase significantly (by an additional 30 words), as the processor must use a function call to evaluate the mathematical comparisons. 54 minutes should be good enough in this example application.

Fig.4 shows the flowchart for the ‘delay 3s, flashing LED’ stub. It’s more complicated than the previous flowchart but is the final one required – everything show here can be easily translated into code. That code is shown in Listing 3 and brings our final code space utilisation up to 170 words, and 13 bytes of RAM. That’s just 33% of the available code space!

Loading the code onto the breadboard circuit, it operates as expected. When left to run, it powers down after 30 minutes and 37s – that’s 37s longer than desired, but that’s accurate enough for a handcrafted 50ms delay function – we are very happy with that result.

Power

Monitoring the current consumption with an accurate multimeter, the ‘on’ current is 30mA. This is to be expected, it’s the current drawn by the LEDs. Once the circuit has powered off the current consumption falls to 0.0015µA – less than 2nA! That’s very impressive. The circuit is still functioning, waiting for a button press, but draws essentially no current.

Conclusions

It’s surprising how those five simple requirements turned into a design spanning three fairly complicated flowcharts. They key though, is that those flowcharts were detailed enough to enable a direct translation to code, at the lowest level. Turning this design into an assembly language project (to compare with how well the ‘C’ language performed) would be a trivial exercise – perhaps someone

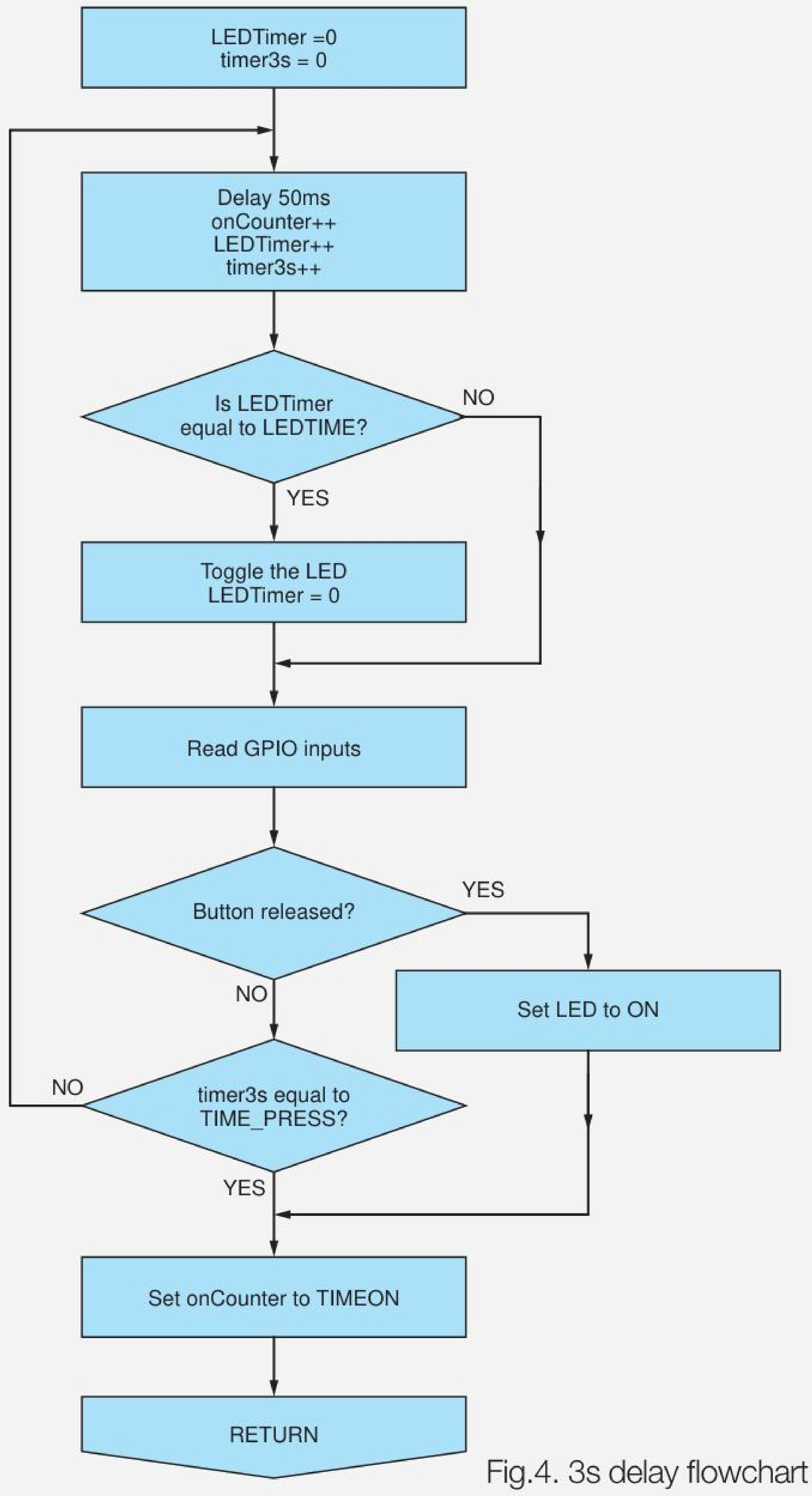

Fig.4. 3s delay flowchart

would like to try and show us the resulting code and data utilisation! If you do, post it up on the **EEWeb.com** forum.

It's worth mentioning that this design and corresponding implementation are in no way the only solution to this problem. Even using the same analytical techniques, there are many other designs that could be created, and there could easily be better ones. This one was quick to implement and works well, fitting into the space available on the device – we are happy!

It's been an interesting exercise over the last three issues to have taken this through from an idea, to clearly stating the requirements, then on to flowchart design and finally coding – with the coding being the simplest part of the exercise. This is the way software design should be. It's also encouraging how few code instructions were required for each flowchart. This is because flowcharts mainly show flow of control in a program, and flow of control is cheap in terms of code space. The most complex function used in this project is the delay function; everything else is reading and writing to the odd register here and there, and a few GPIO writes. Not all programs work out to be this simple, but when designing projects with a small processor, you already know that the problems are simple – otherwise you would have used a bigger microcontroller from the start. All the same, there are some complex behaviours in this project and the PIC10F202 met the challenge well, with room to spare!

This now gives us the courage to be more adventurous with our project ideas... let's see what surprises next month brings!

Listing 2: Source code for Power-on

```
// LED to ON, Power to ON
GPIO = 0x01;

// Delay for a few seconds to
// avoid key de-bounce
delay_50ms(40);

onCounter = 40;

do {
    // Have we been on long enough?
    if (onCounter >= TIMEON) {
          // LED to OFF, Power to OFF
          GPIO = 0x04;

          // Sleep
          asm(“SLEEP”);
    } else {
          delay_50ms(1);
          onCounter++;

          // Read GPIO
          pinStatus = GPIO;

          // Is the push button low?
          if ((pinStatus & 0x02) == 0) {

                // Delay for 3s, flashing LED

          }
    }
} while (1);
```

Listing 3: Source code for 3s delay

```
// Delay for 3s, flashing LED
// ==========================

LEDTimer = 0;
timer3s = 0;

do {
    delay_50ms(1);
    onCounter++;
    LEDTimer++;
    timer3s++;

    if ( LEDTimer == LEDTIME) {
          // TOGGLE LED TBD
          GPIObits.GP2 = !GPIObits.GP2;
          LEDTimer = 0;
    }

    // Read GPIO
    pinStatus = GPIO;

    // Button released?
    if (pinStatus & 0x02) {
          GPIObits.GP2 = 0;
          break;
    }
} while (timer3s < TIME_PRESS);

if (timer3s == TIME_PRESS)
    onCounter = TIMEON;
```

Max's Cool Beans

By Max the Magnificent

Fixing BOB's dynamic range

As you may recall, the current version of my *Awesome Audio-Reactive Artifact* (**https://bit.ly/2G86DLJ** and Fig.1) employs an ADMP401-based breakout board (BOB) from SparkFun (**https://bit.ly/1RdknR3**). This works really well, and it has the advantage that we can connect the output from the BOB directly to the audio input of a seven-band graphic equaliser IC, the MSGEQ7 (via a 22kΩ resistor and 100nF decoupling capacitor).

The only problem with this BOB is that it doesn't support a wide dynamic range. It's OK with a reasonably robust sound source, but it doesn't respond well to low-level sounds in a quiet room, and it tends to saturate with overly loud sounds.

What we really want is a system that, in a noiseless environment, responds enthusiastically to a click of the fingers or a softly spoken word from halfway across the room. Alternatively, if we're playing our music with gusto and abandon, we still want the system to respond in a meaningful way; ie, we don't want it to saturate and drive the LEDs full-on.

Divide and conquer

The next option we discussed is to employ the MAX9814-based microphone plus amplifier BOB with integrated auto-gain control (AGC) (**https://bit.ly/2FVmMVZ**). The idea behind AGC is to use closed-loop feedback to maintain a suitable signal amplitude at the output, despite variation of the signal amplitude at the input, thereby enabling the circuit to work with a greater range of input signal levels.

One problem with this BOB is that its output is 2V$_{pp}$ (peak-to-peak) with a 1.25V DC bias, but the MSGEQ7 only requires 300mV$_{pp}$. We solved this in my previous column by front-ending the MSGEQ7 with a simple voltage divider circuit.

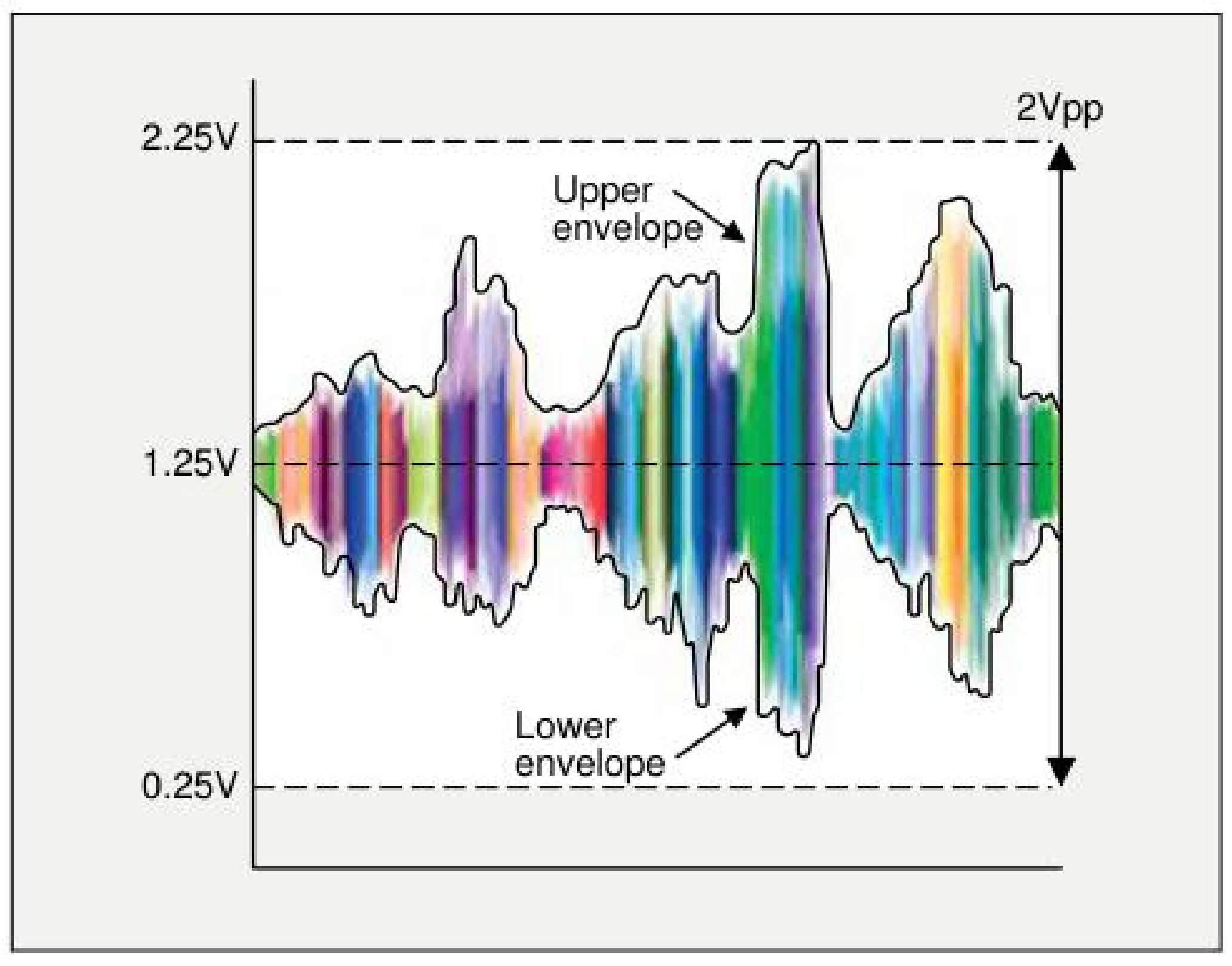

Fig.2. Envelopes superimposed over the audio signal.

No gain without pain

If we use the MAX9814-based BOB as-is, then its default gain is 60dB (1000). However, the BOB also has a master GAIN control input. If we connect this to one of the Arduino's digital pins and set the pin mode to OUTPUT, then driving the pin LOW or HIGH will cause the BOB to change its gain to 50dB (~316) or 40dB (100), respectively. (Setting the Arduino's pin mode to INPUT will return the BOB to using its default 60dB gain).

In order for the Arduino to know what it needs to do, it has to have some clue as to what is coming out of the BOB. If the master gain is currently set to 40dB, for example, and the audio output from the BOB is insignificant, then the Arduino may decide to increase the gain to 50dB or 60dB. Alternatively, if the gain is currently set to 60dB and the output from the BOB is a constant 2V$_{pp}$, then the Arduino may decide to drop the gain to 50dB or 40dB.

Fig.1. *Audio-Reactive Artifact* project in action

One solution would be to feed the output from the BOB directly into one of the Arduino's analogue inputs and to perform all of the processing in software. In this case, no extra components are required; also, it's easy to make changes. On the other hand, things aren't quite as simple as we might hope, because we will have to accommodate the fact that the audio signal is oscillating above and below the DC bias value. Also, we will have to address the fact that when we sample the signal, we might happen to hit a high spike in an otherwise low signal, or vice versa.

Pushing the envelope

When we talk about the 'envelope' of an oscillating signal, we are referring to a smooth curve outlining its extremes, thereby generalising the concept of a constant amplitude. Consider a representative signal coming out of the MAX9814-based BOB, over which we might superimpose outlines to represent the upper and lower envelopes (Fig.2).

Now suppose that we could create a simple circuit that could accept the audio signal as input and generate a voltage signal representing the upper envelope as output. Happily, such a circuit exists, and it's illustrated in Fig.3.

For diode D1, which acts as a half-wave rectifier, we could use a generic 1N4001 if that's what we happen to have lying around, but – if we have a choice – we might opt for a small-signal diode like a 1N4305 or 1N4148.

If we feed this output to one of the Arduino's analogue inputs, it will make our lives a lot easier when it comes to writing the code to control the BOB's master gain control. The RC network using R3a and C3 forms a simple filter, where the component values have been selected to smooth any spikes while still following the overall envelope. Resistor R3c is used

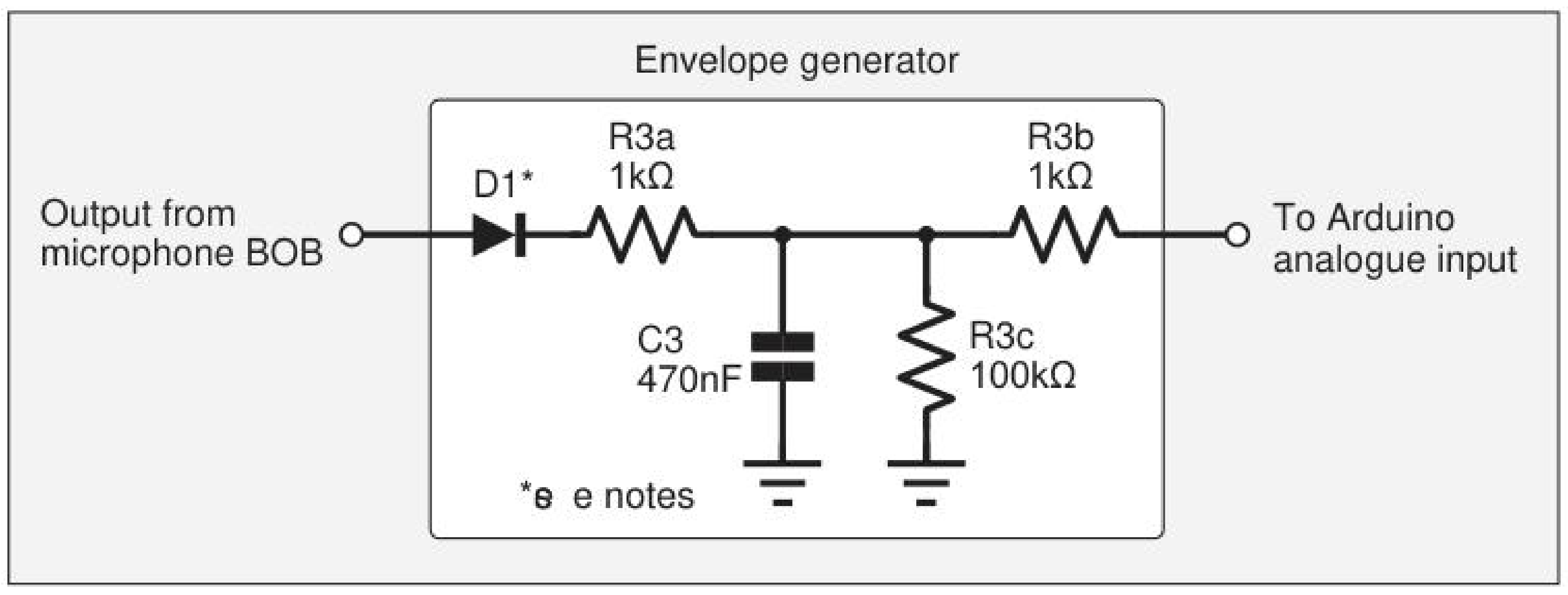

Fig.3. Envelope generator circuit.

to discharge the capacitor, while R3b is used to protect the Arduino's input.

Let's assume that the voltage drop of the diode is 0.7V. Thus, even without an audio signal, the capacitor will charge to a constant value of 1.25 – 0.7 = 0.55V, and the 0V to 1V envelope from the half-wave rectified audio signal will be superimposed on top of this.

If we bring everything together, the resulting circuit is as shown in Fig.4.

In the fullness of time, I'm thinking of creating my own small board that combines everything excluding the Arduino, thereby giving me an easy-to-use solution for any future audio-reactive projects (I do have a few ideas up my sleeve).

Last, but not least, we should perhaps note that the component values shown in Fig.3. were derived from 'back of the envelope' (no pun intended) calculations. We may end up fine-tuning these values when we get to see what's happening using an oscilloscope. Until next time, have a good one!

If you are interested in learning more, I've discussed all of this in excruciating detail in two columns on **EEWeb.com**: *Best MEMS Microphone for use with the MSGEQ7* (**https://bit.ly/2X4cyby**) and *Audio Envelope Generating Circuit for Use with the MSGEQ7* (**https://bit.ly/2UOAbaL**).

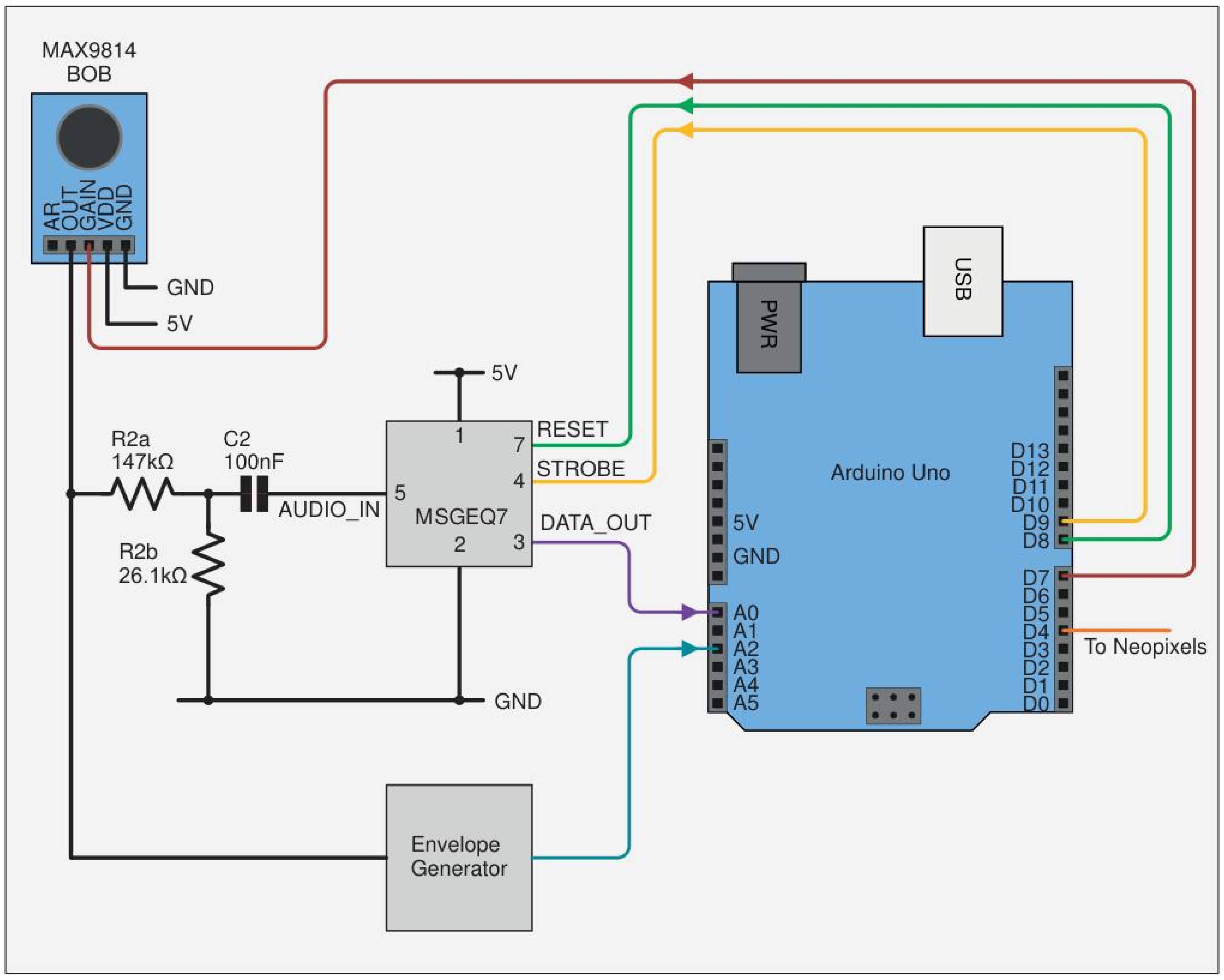

Fig.4. The dynamic-range-fixing circuit – I'm tempted to say, 'BOB's your unc...', maybe not.

Cool bean Max Maxfield (Hawaiian shirt, on the right) is editor-in-chief at **EEWeb.com** – the go-to site for users of electronic design tools and askers of electronic questions.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

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Make it with Micromite

Phil Boyce – hands on with the mighty PIC-powered, BASIC microcontroller

Part 6: Micromite-controlled Electronic Dice

This month, we will bring together many of the techniques we've learnt so far to create our first mini-project: an *Electronic Dice*. This project neatly demonstrates the digital input and output techniques covered in *Parts 4 and 5*, and introduces a few new commands for generating a random number. We will also learn how to load a (long) program listing from a computer directly into your Micromite, rather than typing it in line by line into the EDITor.

The *Electronic Dice* comprises a single button (digital input), 7 LEDs (digital outputs), and also an infrared receiver (another digital input). Pressing the button causes the LEDs to display a spinning effect, after which a random number (between 1 and 6) is displayed as a dice pattern on the LEDs. Another press of the button will start another spin effect with a new number being displayed. If the button is not pressed for few seconds, then all the LEDs will turn off. Pressing the button again at any stage will restart the whole process.

The *Electronic Dice* is a very simple circuit that can be built on a small piece of stripboard. Building it is a worthwhile learning exercise and if you don't want to fully understand how the code works at this stage then that is just fine; simply jump to the *Construction* section. However, if you do want to understand the project's theory of operation then please read on…

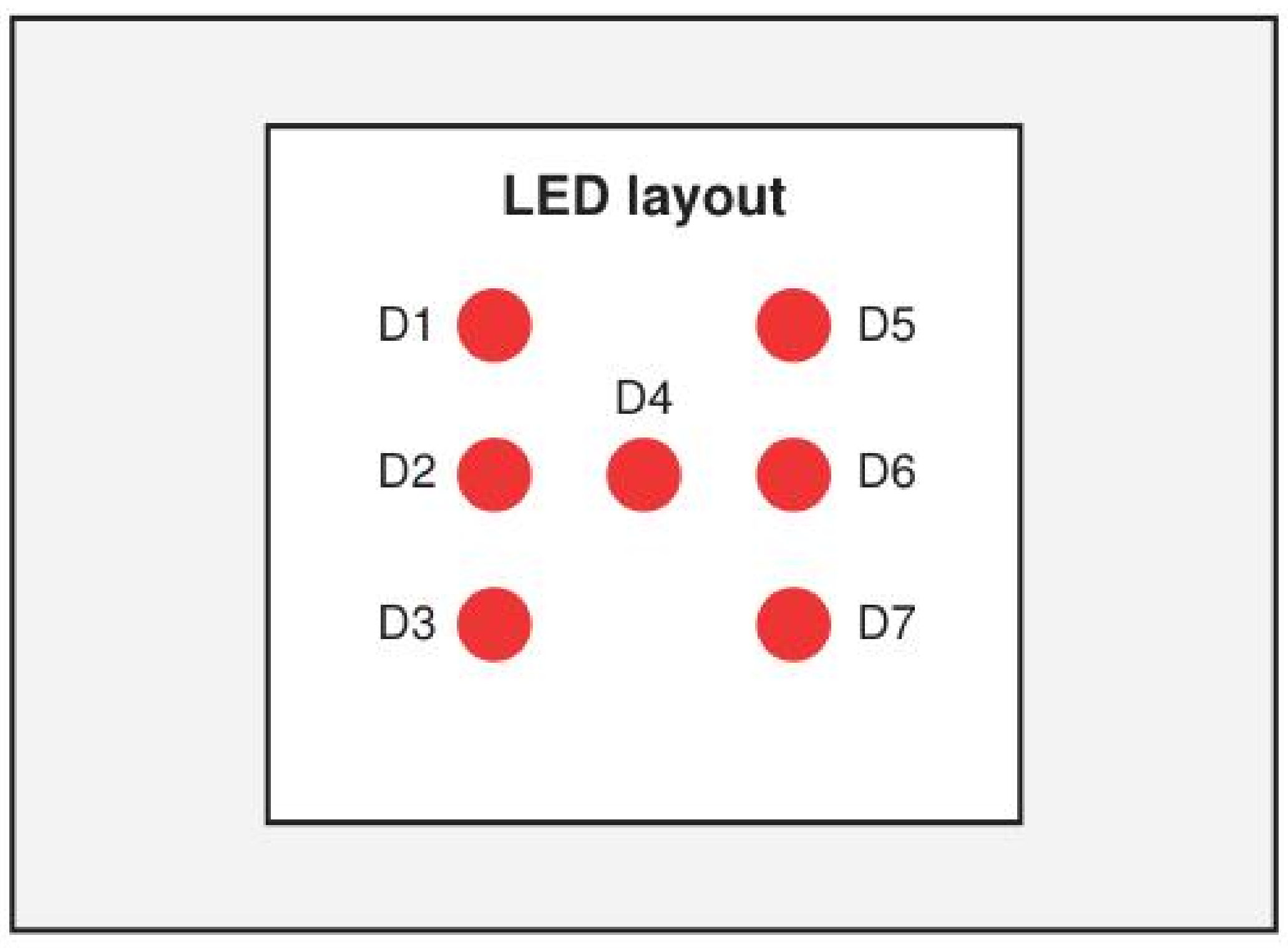

Fig.1. Required layout of the 7 LEDs to be able to display any dice number.

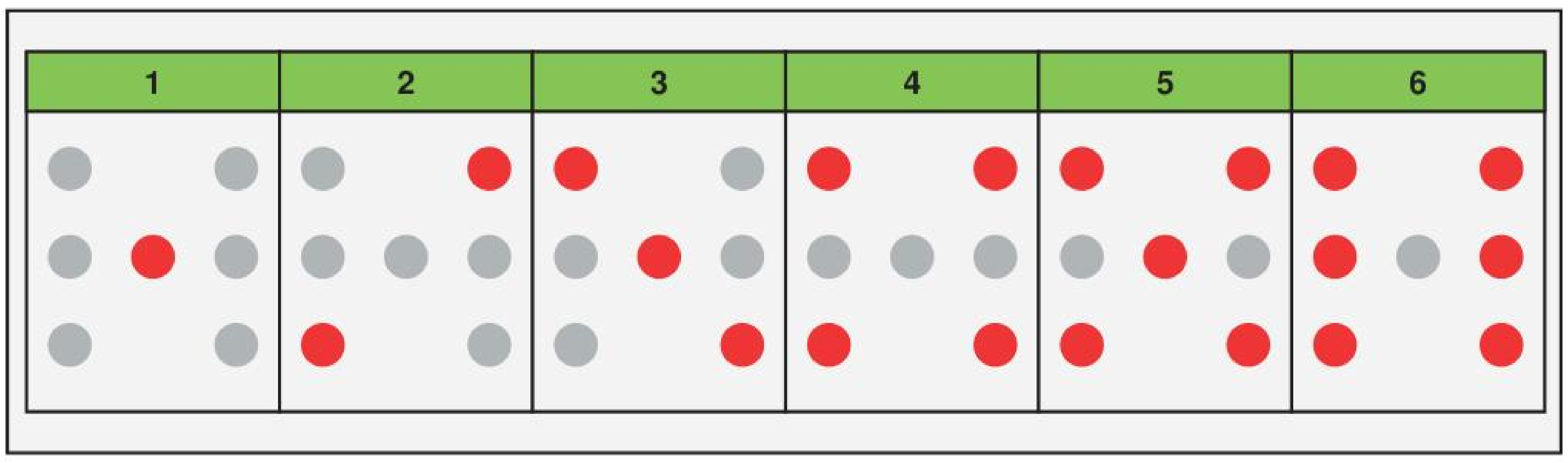

Fig.2. The six possible LED dice patterns.

Dice theory

To create an *Electronic Dice* we need seven LEDs laid out as shown in Fig.1. This allows any of the familiar six dice numbers to be displayed by lighting the appropriate combination of LEDs, as shown in Fig.2. A closer examination of Fig.2 shows that some of the LEDs can be paired-up; for example, whenever D1 is lit, then D7 is also lit. There are actually three such pairs of LEDs: D3+D5, D2+D6, and D1+D7 (see Fig.3). Note that the central LED (D4) cannot be paired up because to display the value '1', no other LED is needed; however, for discussion purposes we will refer to four pairing patterns: A, B, C and, also D.

Now let's look at each of the six possible dice patterns, this time considering which pairs need to be turned on. Referring to Fig.4, you can see that to display the value '2', we just need to turn on pair A. For '4', turn on pairs A and C; and for value '6' turn on pairs A, B and C. The important point to note here is that with the appropriate combination of up to three LED pairs, we can display any of the six possible dice patterns.

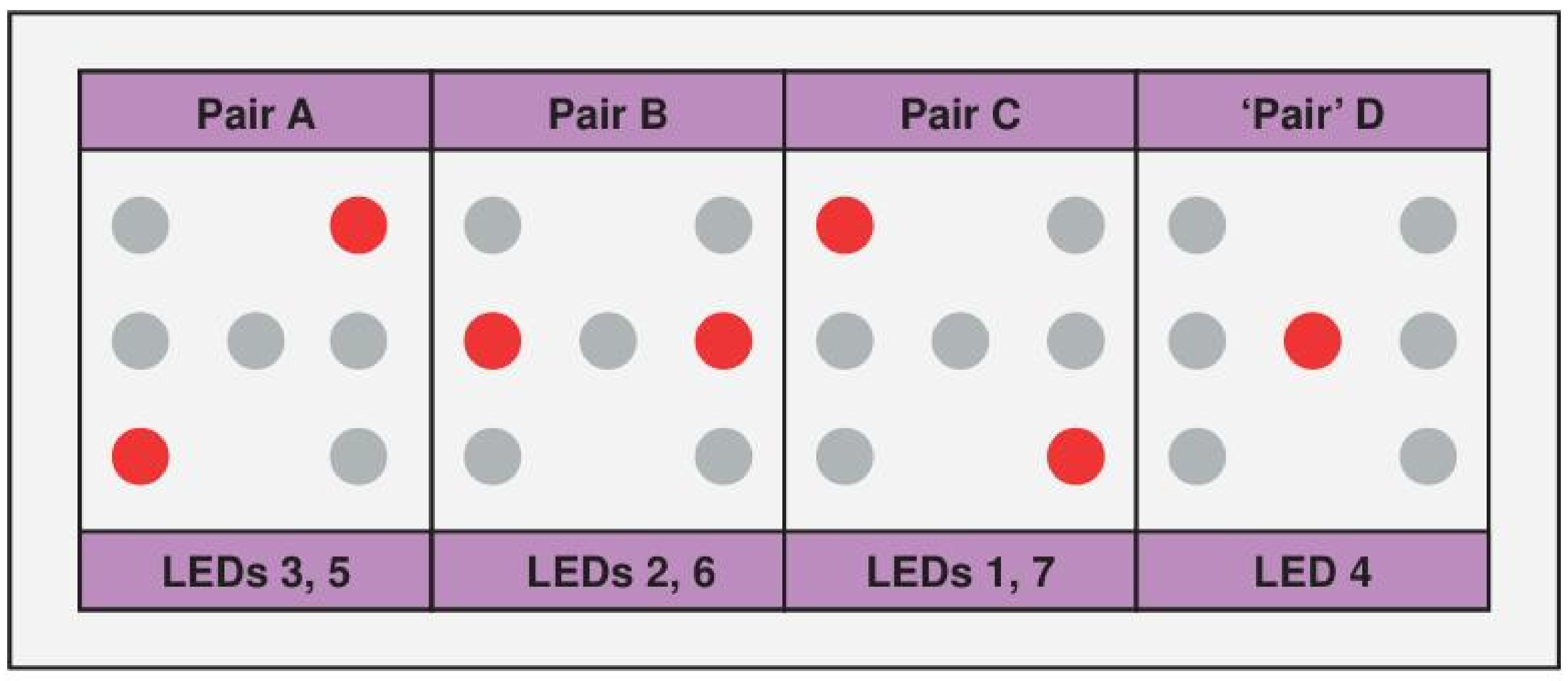

Fig.3. How the LEDs can be paired.

How many I/O pins to control seven LEDs?

We could easily have used seven I/O pins (configured as outputs) and had each one connected to a single LED (and current-limiting resistor). However, by pairing the LEDs as discussed above, we could reduce the requirement to four outputs. In fact, we will use an additional trick to reduce this down to just three output pins.

In *Part 4*, we discussed how to connect two LEDs back-to-back to two digital output pins; the circuit is repeated here in Fig.5. It was mentioned that we could expand on this technique, and along with appropriately switching the I/O pins on and off, we can actually save the total number of I/O pins required to control multiple LEDs. To recap, if point X (in Fig.5) is at +V (ie, on), and point Y is at 0V (ie, off), then D1 will be lit. Swapping things over to set point X off, and point Y on will result in D2 being lit. However, with points X and Y both on, or both off, then neither LED will be lit.

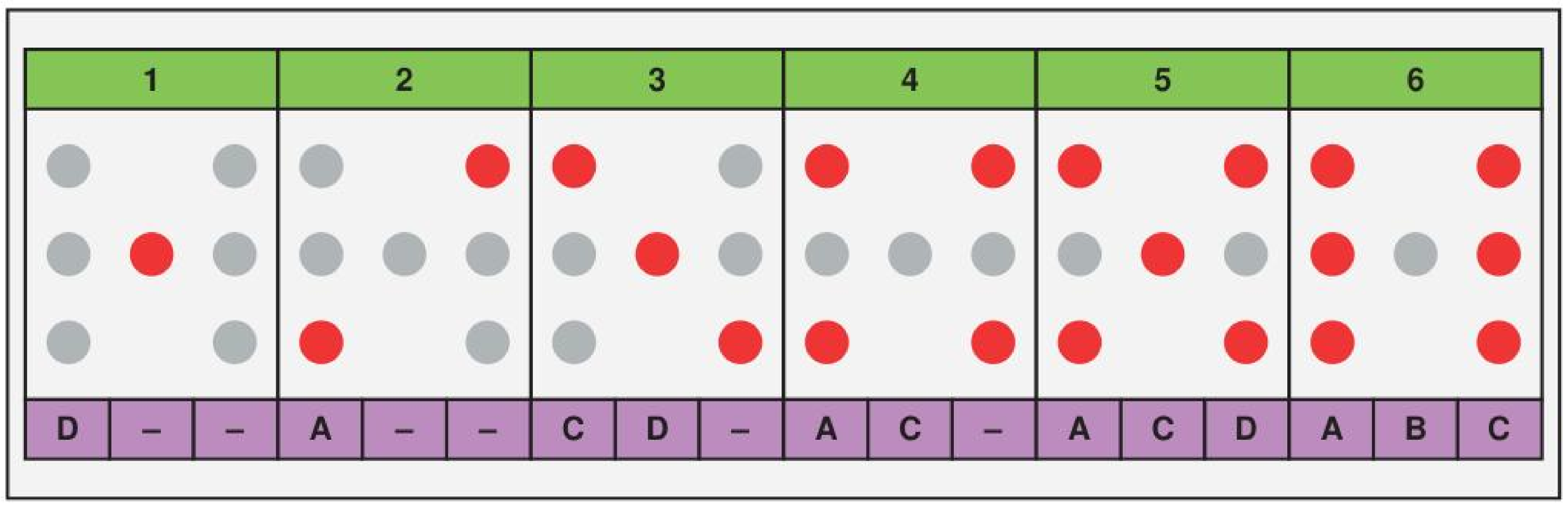

Fig.4. The six possible LED dice patterns as pairs.

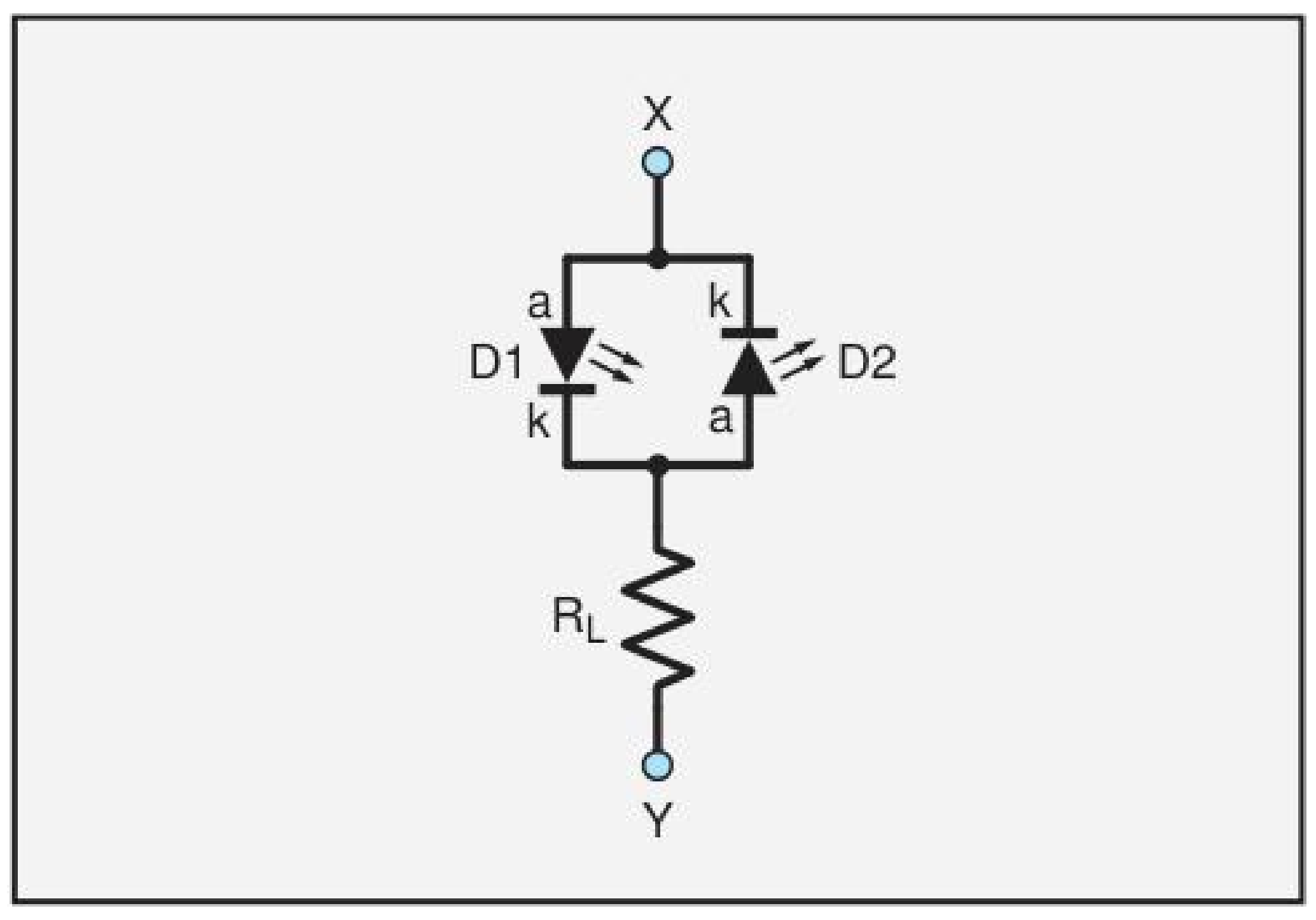

Fig.5. Back-to-back LEDs connected to two I/O pins.

At this point it is worth referring to the circuit diagram for the *Electronic Dice* – see Fig.6. Here you can see how the seven LEDs are back-to-back connected to just three I/O pins (4, 5, and 6). Note that there are just four current-limiting resistors too (R1-R4). It is important to understand that each of the two back-to-back LEDs are *not* a dice pair.

By appropriately switching output pins (4, 5, and 6) on or off, we are able to display any one of our four pair patterns (A, B, C, or D). Let's begin by considering pins 4 and 6 off, and pin 5 on. With pins 4 and 6 off, LEDs D1, D2, D6, and D7 will not be lit; however, with pin 5 on, LEDs D3 and D5 will be lit (and D4 will be off). You will see that D3 and D5 is our pair A.

So, if we use the **PORT** command (introduced last month), we are able to turn on pair A by simply using the code: **PORT(4,3)=&b010**. As a recap; the right-most binary digit is applied to pin 4, the middle binary digit to pin 5, and the left-most binary digit to pin 6.

So for completeness, Pair B is **PORT(4,3)=&b011** (ie, pins 4 and 5 on, pin 6 off), Pair C is **PORT(4,3)=&b100**, and Pair D is **PORT(4,3)=&b101**

If this seems confusing, then don't panic – I would simply recommend moving on to building the circuit, and then typing the above four **PORT** command values (not forgetting to include **SETPIN(x),DOUT** first for pins 4, 5 and 6). This will show everything nicely (and will also confirm that the circuit has been assembled correctly).

We now have four **PORT** values, meaning that we can display any of our pairs. All we need to understand now is that as discussed above, up to three pairs need to be used to show any dice value between 1 and 6. We will be using persistence of vision, and continually (and rapidly) switch between three **PORT** values to make the LEDs show any value; more on this later when discussing the program code.

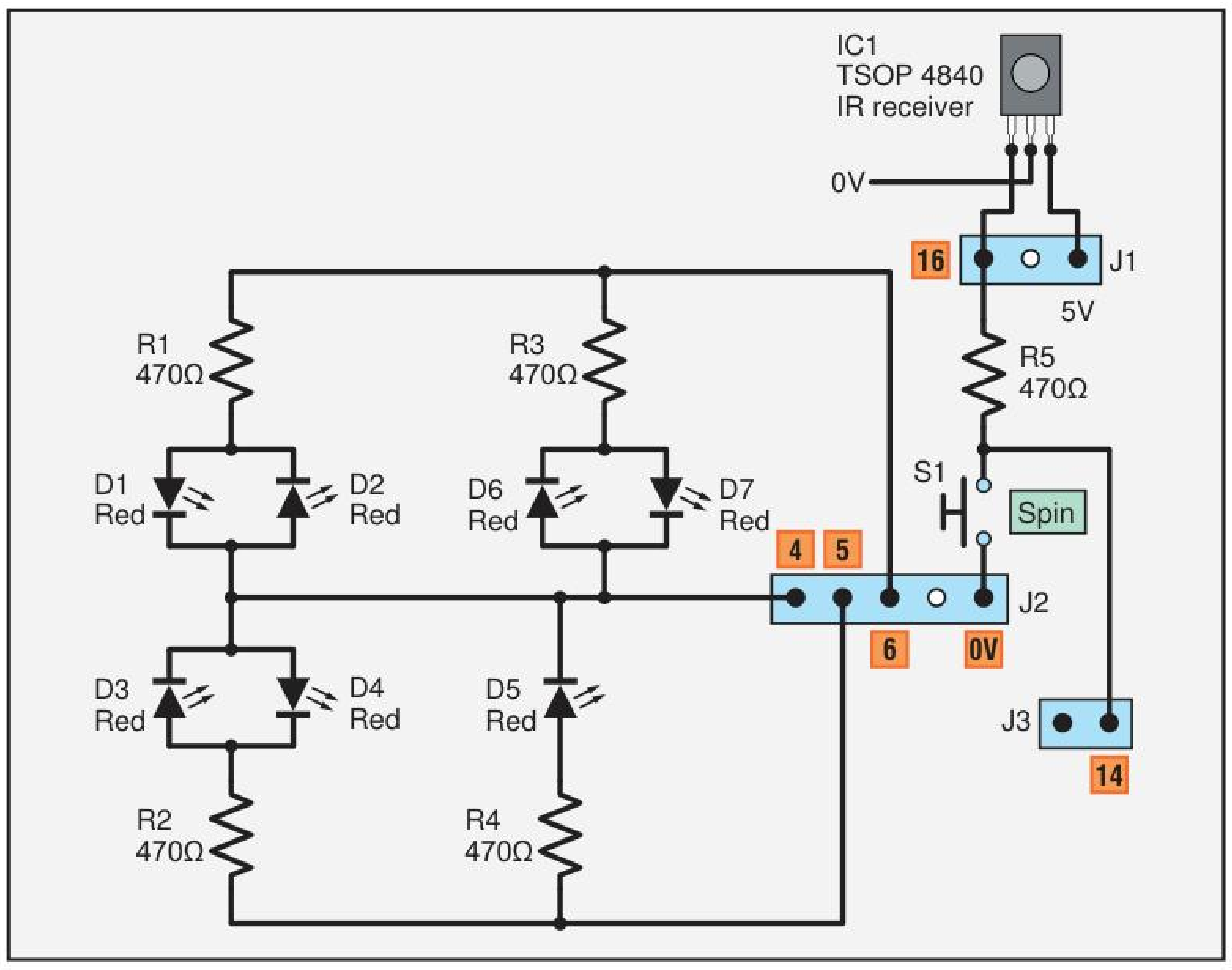

Fig.6. Circuit diagram for the *Electronic Dice*.

Electronic Dice inputs

Now that we have the basis for displaying any dice value on the seven LEDs, we next need to consider what else will be required. We will use a button (connected to a digital input pin) to 'spin' the dice; and an IR receiver will also be incorporated. Both of these can be seen in the circuit diagram (Fig.6). However, there is one more piece of functionality we need – a random number generator.

Generating a random number

In MMBASIC there is the command **RND()** which can be used to generate a random number between 0 and 0.999999. To see this in use, connect up your *MKC* and *DM* to your computer, and start TeraTerm (remembering to connect to the correct COM port and at the correct baud speed). At the command prompt, simply type the following:

```
PRINT RND()
```

You will see a number displayed, for example 0.69; however, this is not a lot of use for our *Electronic Dice* because we need to generate a number between 1 and 6. Now, if we were to multiply the random number generated by 6 (ie, multiply the random number by the upper value of what we need) then we will be closer to what we want. So type:

```
PRINT RND()*6
```

This time you will see something displayed like 3.03251; the actual answer could be anywhere between 0 and 5.99999. So now we just need the integer part (and drop all the decimal-place digits). To do this we can use the **INT()** command to extract the integer part as follows:

```
PRINT INT(RND()*6)
```

Now something like '3' will be displayed – this is more like it; however, the value returned will be from 0 to 5. So finally we need to add 1 to the answer to give us an integer value between 1 and 6. To see this, type:

```
PRINT INT(RND()*6)+1
```

For future reference, whenever we need a random number between 1 and **x**, we simply use: **INT(RND()*x)+1**

But just how random is RND?

I love this question and I have borrowed it from the classic *80 Micro* magazine; a

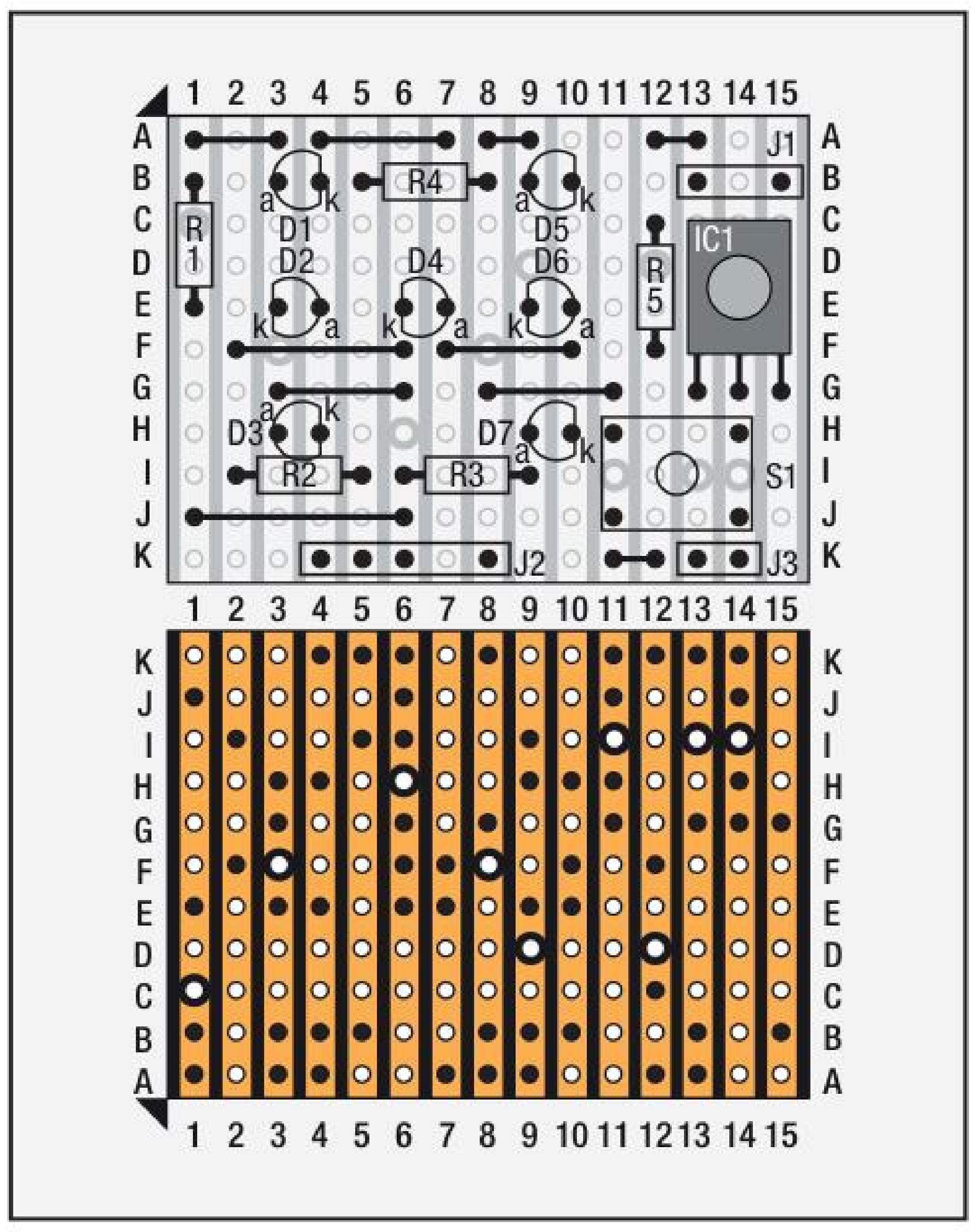

Fig.7. (Top) Stripboard layout for the *Electronic Dice*; (below) copper track view showing track cuts.

popular magazine back in the 1980s about the brilliant Tandy TRS-80 computers. In fact, it was thanks to this magazine, and my father, who had just purchased a fully kitted out TRS-80 model III computer, that as a child I developed my love for all things BASIC.

Back to the question – if you tried the `PRINT RND…` commands above, then you may have been surprised as to how I was able to 'predict' the random numbers you saw generated. It is to do with the fact that when the Micromite is powered up (or re-booted), it will follow a precise set of instructions (and also the same set of instructions) every time. Now, when the first request for a `RND` number is made, it will be following the same sequence of events and show the (pseudo-) random result. You can try this simply by resetting the Micromite, and type `PRINT RND()` and write down the result. Then `PRINT RND()` two more times (writing down the other two results). Now reset the Micromite, repeat the above and you will see the same sequence of three 'random' numbers.

So these 'random' numbers are actualy following a pattern, and if we relate this back to our Micromite *Electronic Dice*, then each time we power up (or reboot), we'll see the same sequence of numbers generated. It's a bit like buying a book of random numbers (yes, that's a real thing! **http://bit.ly/pe-jul19-miwm**) – even if the numbers are genuinely random, if you repeatedly use the first page of numbers they will simply repeat. What we ideally need to do is to make `RND` more random!

In BASIC, the command `RANDOMIZE x` is used to re-seed the `RND` number generator (with the value `x`). However, if we are not careful then using this can potentially still lead to the same sequence of random numbers being generated if we always use the same value for `x`. The preferred way to use `RANDOMIZE` is in conjunction with a timer. In MMBASIC there is the Timer variable (which counts the number of milliseconds (ms) since power-up, or since re-boot). Being a variable, we can also alter the value of Timer with `TIMER=x` (after which it would continue to count up from the new value). Now if we use `RANDOMIZE TIMER` to re-seed the random number generator, then we will see a much more random-looking sequence of numbers generated. Try this by resetting the Micromite, then typing `RANDOMIZE TIMER`, and then three lots of `PRINT RND()` (as you did before). You will now see a different set of answers. Reset and repeat, and you'll again receive three different answers.

This is the technique we will use to prevent the same sequence of 'rolled dice' values appearing. We now have all the building blocks required to create our *Electronic Dice*.

Electronic Dice circuit description

The circuit diagram for the *Electronic Dice* is very simple as can be seen Fig.6. The seven LEDs (D1-D7) are connected to three I/O pins (4, 5, and 6) in such a way that allows us to display any dice-number pattern (as discussed above). Four current-limiting resistors (R1 to R4) are required to protect the LEDs. Connection to the LED I/O pins is via connector J2; this also gives us the required 0V connection.

The Spin button (S1) is connected to I/O pin 14 via connector J3 – we simply read the value of pin 14 to check whether the button is pressed (ie, value=0) or not (value=1). The IR receiver needs to be connected to I/O pin 16 (as discussed last month) and also requires a +5V supply. The two pins on J1 provide these two connections. Finally, R5 protects certain IR receivers should the Spin button be pressed at the same time as an IR signal is received. As with any Micromite hardware project, the intelligence is added via the program code (and that will be discussed shortly).

Electronic Dice construction

Construction is fairly straightforward – the circuit is built on a small piece of stripboard, 15 tracks wide, with 11 holes in each track – see Fig.7. Start by cutting out the stripboard, and use a file to smooth off all the edges. You may also find it useful to round off the corners to remove any sharp points. Next, mark out the locations of the nine required track cuts – then check and double-check all of these before making the cuts. Once the cuts are made, proceed with installing the ten wire links, ensuring you don't introduce any shorts to neighbouring tracks.

Next, install the five 470Ω resistors, again making sure you don't introduce any shorts. Now add the seven LEDs, taking care that the LEDs are inserted with the correct orientation. The shorter cathode lead (k) on each LED needs to be inserted into the correct holes, as shown in Fig.7. Take your time to ensure you get all seven correctly oriented. Now insert the IR receiver – carefully bend the three legs at right angles (close to the body of the receiver) ideally using long-nosed-pliers, and insert into holes G13, G14, and G15.

The last components to solder are the button, and the three header connectors. J1 is a 3-way part, but with the middle pin removed. Use the same technique as when assembling the *Development Module* (*Part 3*, *PE*, April 2019, page 64, Fig.5); in other words, push the shorter side of the pins towards the black plastic housing so that the pins fully extend out from the other side. Then insert the connector (pins into the component side) so that the pins extend down and out from the solder side. Solder a single pin to begin with so that you can ensure the pins are at right angles to the board. Repeat for the other two connectors – J2 is a 5-way piece with the forth pin removed, and J3 is a 2-way. The end result should be an *Electronic Dice* module that can be plugged into the *MKC* and *DM*.

Before going any further, visually check that there are no shorts between any neighbouring tracks – a multimeter set to continuity can be useful for this. If you see anything that isn't correct, then make sure you fix it before continuing with the next stage.

Electronic Dice testing

Plug the *Electronic Dice* module into your *Development Module* (*DM*). Note that there is no need to remove power from your *MKC* when plugging in the *Electronic Dice* module. The Spin button should be towards the right, and the right hand pins on J1 and J3 should line up nicely with the two right-most pins on the *DM*. Take your time and ensure it is inserted correctly.

Now with everything connected to your computer, ensure you can start TeraTerm and connect to your *MKC*/*DM*. If this fails, then disconnect from your computer and re-check everything.

Once you have a connection in TeraTerm, type the following two lines of code at the command prompt:

```
SETPIN(4),DOUT:SETPIN(5),DOUT:SETPIN(6),DOUT
PORT(4,3)=&b101
```

This should result in the middle LED being lit (ie, the dice value '1'). If so then move on to typing the following, one line at a time:

`PORT(4,3)=&b010`	Should display Pair A (D3 and D5) which is the value '2'.
`PORT(4,3)=&b011`	Should display Pair B (D2 and D6)
`PORT(4,3)=&b100`	Should display Pair C (D1 and D7)

If you don't see the correct LEDs light up then you either have a short somewhere, or one (or more) LEDs is inserted incorrectly. To test the Spin button, type in the following two lines:

```
SETPIN(14),DIN
DO:PRINT PIN(14):LOOP
```

You should see a value of '1' showing repeatedly in the TeraTerm screen. Whenever you press the Spin button, this should change to '0'. Go ahead and test this. If there is no change when the button is pressed then something is wrong. If the value '0' is always displayed then there is a short (to 0V) somewhere on pin 14. If the value '1' is always displayed then the button is not responding correctly. Once again, a visual check should rectify any issues.

Next, (and with the two lines of code still showing '1's repeatedly on the TeraTerm screen) press a button on any available IR-remote control transmitter. You should see the value very briefly 'flicker' between '1' and '0'. If there is no change, then check the IR receiver (IC1) and also the adjacent resistor (R5). It is also worth trying a different IR-based remote control.

Finally, press `Ctrl-C` to stop the above; then re-enter the above two lines, but with the value 16 (instead of 14), as follows:

```
SETPIN(16),DIN
DO:PRINT PIN(16):LOOP
```

Again, the TeraTerm screen should repeatedly show the value '1', and change to '0' while the Spin button is pressed, or flicker between '1' and '0' if a button on an IR-remote is pressed. If there is no change, then once again, check the IR-receiver, R5, and the solder joint to pin 16 (on J1).

Once all the above tests have completed successfully, then it is time to enter the *Electronic Dice* program into your *MKC*. However, there are quite a few lines of code to type, so let's now learn how to load a program directly into a Micromite by using copy and paste.

Loading a program directly into the MKC

The method discussed here will use Windows Copy and Paste; and also the MMBASIC command **AUTOSAVE**. An overview of the six steps involved is as follows:

1. Download the *Electronic Dice* program
2. Open the *Electronic Dice* program in a text editor
3. Select All, and Copy to Windows clipboard
4. At the command prompt (in TeraTerm) type **AUTOSAVE**
5. Paste clipboard (ie, the program) into TeraTerm
6. `Ctrl-Z` to commit the program to the Micromite memory.

At first glance, this may appear complex, but once you have done this a few times it becomes a very quick process. Some of you may find the above steps enough of a guide to continue by yourself; however, I will now go into more detail for each step for anyone needing further guidance:

Step 1

To obtain the *Electronic Dice* program, go to the July 2019 issue's page on the *PE* website and download that month's zip file. Inside the package you will find **ElectronicDice.txt** – save it to a convenient folder on your computer.

Step 2

Launch any text editor program (eg, NotePad, WordPad, or even MS Word) and open **ElectronicDice.txt**. You should now see the program as shown in program Listing 1 (but not with colour coding).

Step 3

Use Windows to highlight all the text (with either: Select All, or by using the mouse) and then Copy this onto the Windows clipboard (possibly by using mouse right-click, and then selecting Copy from the menu). You now have the program stored in Windows clipboard.

At this point it is worth clearing any program that may currently be in the Micromite. It is not an essential step – but it helps to better demonstrate what we are doing here. Using TeraTerm (connected to your *MKC*/*DM*), type **NEW** at the command prompt to remove any code currently in the *MKC*. You can check the *MKC* is now empty by pressing F4 (or typing **EDIT**) to enter the EDITor – you should see that there is no code. Now return back to the command prompt (by pressing `Ctrl-C`).

Step 4

At the command prompt, type **AUTOSAVE**. This puts the Micromite into automatic program entry mode.

Step 5

Paste the clipboard (ie, the program) into TeraTerm by using the mouse right-click. Press OK to any pop-up confirmation message and you will then see the program appear in the TeraTerm window.

Step 6

Press `Ctrl-Z` to commit the program to the Micromite's memory. Note that any previous code that was contained in the Micromite will be over-written with the new code that was just pasted.

Now, as a quick check, enter the EDITor (by pressing F4, or by typing **EDIT**) and you will be able to scroll through the program. If this is the case, then congratulations, you have successfully loaded the *Electronic Dice* program into your *MKC*.

Troubleshooting

If nothing was showing in the EDITor then either a step was missed, or a simple mistake was made. The most common mistake is at Step 6, if `Ctrl-C` is pressed instead of `Ctrl-Z`. `Ctrl-C` will abort the program entry and leave the memory unchanged. Simply repeat Step 2 through to Step 6 and you should be able to remedy any issue.

Running the Electronic Dice program

You should now be in a position to run the *Electronic Dice* program. Simply press F2 to run it (or type **RUN** at the command prompt). If all has gone well then you should see the numbers 1 to 6 displayed briefly on the seven LEDs; after which the LEDs will all turn off.

Now press (and then release) the Spin button and you should see the LEDs flicker dimly before displaying a random number. The flickering is just to give the dice a spinning effect. Press the Spin button again and a new number will be displayed (after the spinning effect). Now simply leave the unit for approximately 10 seconds and check that all the LEDs turn off. Finally, press a button on an available IR-remote control and this should cause the *Electronic Dice* to display a new number (in the same way as if you had pressed the Spin button).

Electronic Dice program operation

See Listing 1 with comprehensive comments to help you understand how the program works. Most of the commands should be familiar, but a few details are worth highlighting:

- Commands can be upper or lower case (or a mix of both).
- Variables **s1**, **s2**, and **s3** each contain a binary value used to switch on an LED pair. These pairs are rapidly switched in turn to display a dice value (in the **SUB ShowNum**) by using the **PORT** command.
- The three lines of code: **DO WHILE PIN(14)=0... spin...LOOP** behave like a normal **DO..LOOP** but with the possibility of exiting the **DO..LOOP** when a certain condition is met. Here we repeat the **DO..LOOP** while Pin 14=0 (Spin button pressed). We only exit the loop when Pin 14=1 (Spin button released). When the button is released, the program continues with the line of code immediately after the **LOOP** command.
- The block of code: **SELECT CASE diceNum (...CASE.... END SELECT)** takes the value in variable diceNum (between

- 1 and 6), and then, depending on the value, will load **s1**, **s2**, and **s3** with the LED pairs needed to display the dice number. See the *User Manual* for a thorough explanation of the useful **SELECT CASE** command.
- When the program is run, the values will be displayed on the TeraTerm screen (due to the **PRINT** command).

There is nothing scary in this program – but do email me if you get stuck.

The *Electronic Dice* project shows that with a relatively short program, we can create the necessary logic to run some simple hardware and create a functioning project. An important point to stress here is that by making changes to just the program (keeping the hardware exactly the same) we are able to change the functionality of the hardware. Put it another way, the program code is the 'brains' of the project – something that will be mentioned often throughout this series.

Try making some program changes. For example, shorten the time delay before the LEDs turn off, remove the 'spin effect', and – if you're feeling confident – show two dice patterns for each press of the Spin button (to simulate two dice being 'rolled'). Don't panic if you mess up your code – simply Paste the original **ElectronicDice.txt** program back into your *MKC* (using **AUTOSAVE**). Never be afraid to try new ideas!

Next month

In the next part we will create a simple 'prediction game' and add sound with a piezo buzzer and the PWM command. Plus, we will look at using Micromite with macOS.

Questions? Please email Phil at:
contactus@micromite.org

Listing 1: *Electronic Dice* program (blue: command; red: value; green: string; grey: comment; black: variable, LABELname, SUBname, 'other')

```
' Make it with Micromite
' Mini-Project #1
' Electronic Dice (v1.01)

OPTION AUTORUN ON                               ' Run code on Power-Up (type RUN at Command-Prompt to trigger this)
SetPin 4,dout : SetPin 5,dout : SetPin 6,dout   ' set the 3 correct pins (4, 5, and 6) as Digital OUTputs
SetPin 14,din,Pullup                            ' set Pin 14 as a Digital INput (the 'Spin' button). Active Low (hence PULLUP)

d=500                                           ' set how long a Dice number pattern is shown for on the LEDs
s1=&b101 : s2=&b111 : s3=&b111 : ShowNum        ' At Power-Up, briefly show each of the six Dice number patterns on the LEDs
s1=&b010 : s2=&b000 : s3=&b000 : ShowNum        ' (gives a nice Power-Up demo!)
s1=&b101 : s2=&b100 : s3=&b111 : ShowNum        ' (this is pattern for '3')
s1=&b010 : s2=&b100 : s3=&b000 : ShowNum        ' '4'
s1=&b100 : s2=&b101 : s3=&b010 : ShowNum        ' '5'
s1=&b100 : s2=&b010 : s3=&b011 : ShowNum        ' '6'
Blank                                           ' clears the LED display
d=10000                                         ' increases time that 'Dice Pattern' shown for (ie, acts as a Switch-Off timer)

Do                                              ' main loop here
  Blank                                         ' ensures the LED display is cleared
  waiting:
    If pin(14)=1 then goto waiting              ' waits for the Spin button to be pressed (i.e. =0)
  pause 20                                      ' button pressed - so delay a bit to allow for contact bounce
  Randomize Timer                               ' makes sure random number sequence doesn't repeat (after a Power-Up)
  Do While Pin(14)=0                            ' while button pressed (i.e. =0) . . .
    Spin                                        ' . . . display the 'Spin effect'
  Loop
  diceNum = Int(Rnd(0)*6)+1                     ' generate a random number between 1 and 6
  spinNum = Int(Rnd(0)*5)+1                     ' generate a random number (1-5) for how long to show spin effect
  Print "Dice =";diceNum,"  :  Spin =";spinNum  ' display the random number info on the Console screen
  For x=0 To spinNum                            ' loop the spin affect for the required number of 'spins'
    spin                                        '  . . . liken this to how hard the dice is being thrown!
  Next x

  Select Case diceNum                                  ' depending on random Dice value, show correct pattern on the LEDs
    Case 1 : s1=&b101 : s2=&b111 : s3=&b111 : ShowNum  ' use upto 3 'dot-pairs' (s1, s2, s3) to make correct pattern
    Case 2 : s1=&b010 : s2=&b000 : s3=&b000 : ShowNum  ' D3+D5 ...       ...
    Case 3 : s1=&b101 : s2=&b100 : s3=&b111 : ShowNum  ' D4    ... D1+D7 ...
    Case 4 : s1=&b010 : s2=&b100 : s3=&b000 : ShowNum  ' D3+D5 ... D1+D7 ...
    Case 5 : s1=&b100 : s2=&b101 : s3=&b010 : ShowNum  ' D1+D7 ...  D4   ... D3+D5
    Case 6 : s1=&b100 : s2=&b010 : s3=&b011 : ShowNum  ' D1+D7 ... D3+D5 ... D2+D6
  End Select
Loop

Sub Blank
  Port(4,3)=&b111                               ' setting the 3 LED output pins high will switch off ALL LEDs
End Sub

Sub Spin                                        ' dimly sequence the 3 pairs of LEDs to give a nice 'Spin effect'
 Port(4,3)=&b010 : Pause 1 : Blank : Pause 50   ' Bottom-Left AND Top-Right LEDs on (D3, D5)
 Port(4,3)=&b011 : Pause 1 : Blank : Pause 50   ' Middle-Left AND Middle-Right LEDs on (D2, D6)
 Port(4,3)=&b100 : Pause 1 : Blank : Pause 50   ' Top-Left, Bottom-Right (D1, D7)
End Sub

sub ShowNum                                     ' Rapidly cycle through the 3 'dot-pairs' to create the pattern
  for i = 1 to d                                ' will cycle through for a set number of times
    port(4,3)=s1 : pause 0.1                    ' presistence of vision will make pattern appear 'static'
    port(4,3)=s2 : Pause 0.1
    Port(4,3)=s3 : pause 0.1
    if Pin(14)=0 then exit sub                  ' continually check for Spin button being pressed. If so then Spin again
  next i
end Sub                                         ' if here (Spin not pressed). Will return to start of Do/Loop
                                                ' Start of Do/Loop clears LEDs and waits for next Spin button press
```

Micromite code

The code in this article is available for download from the *PE* website.

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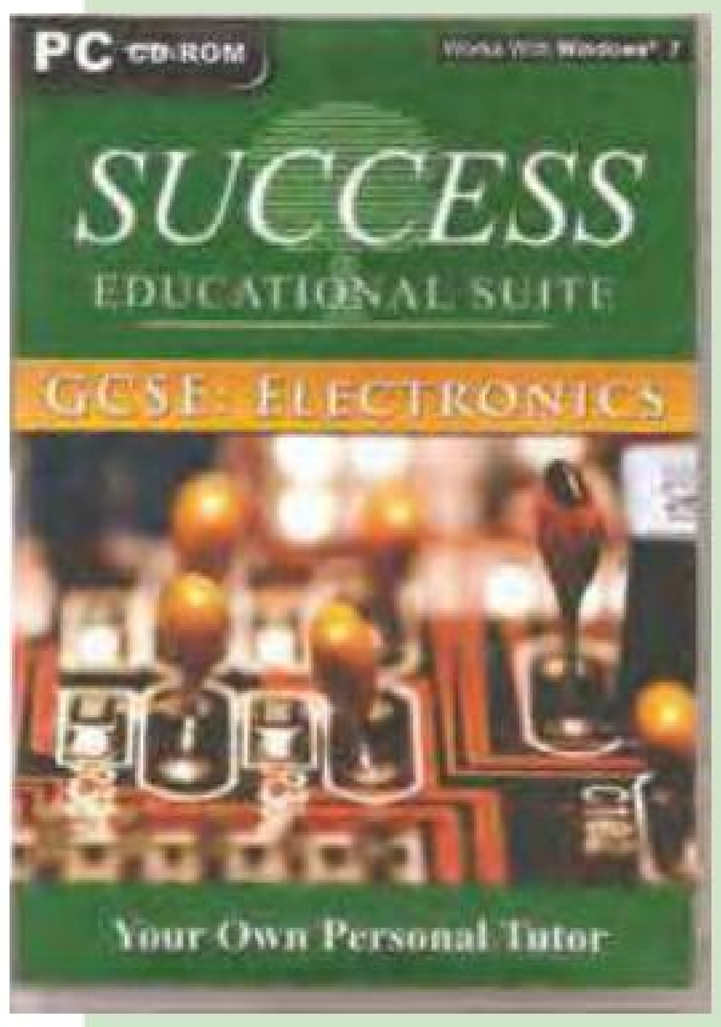

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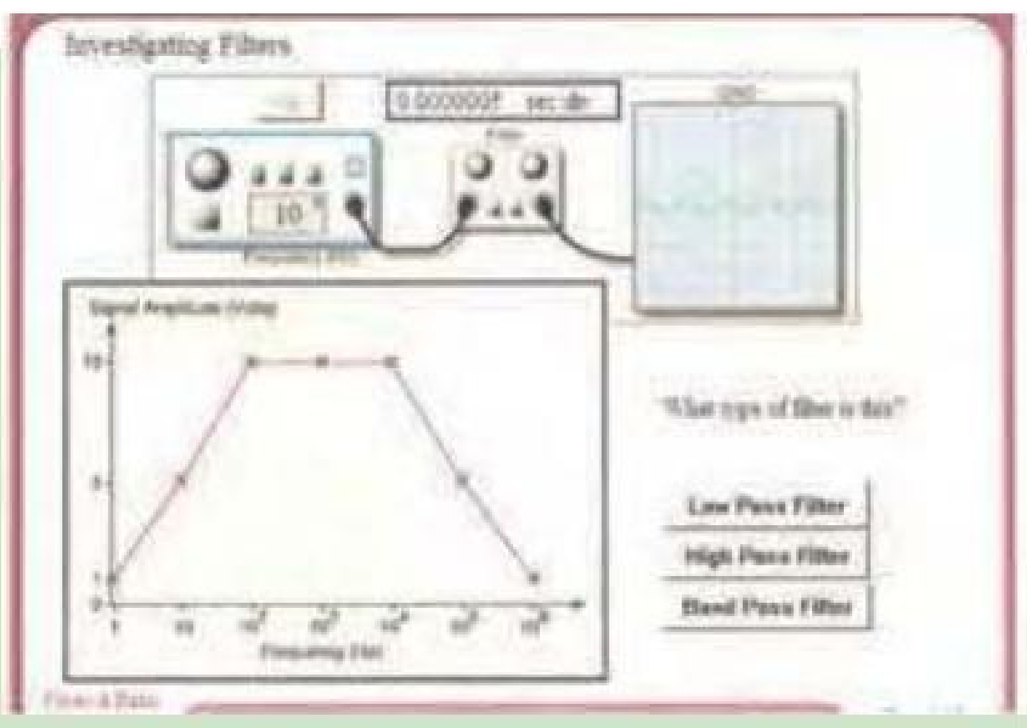

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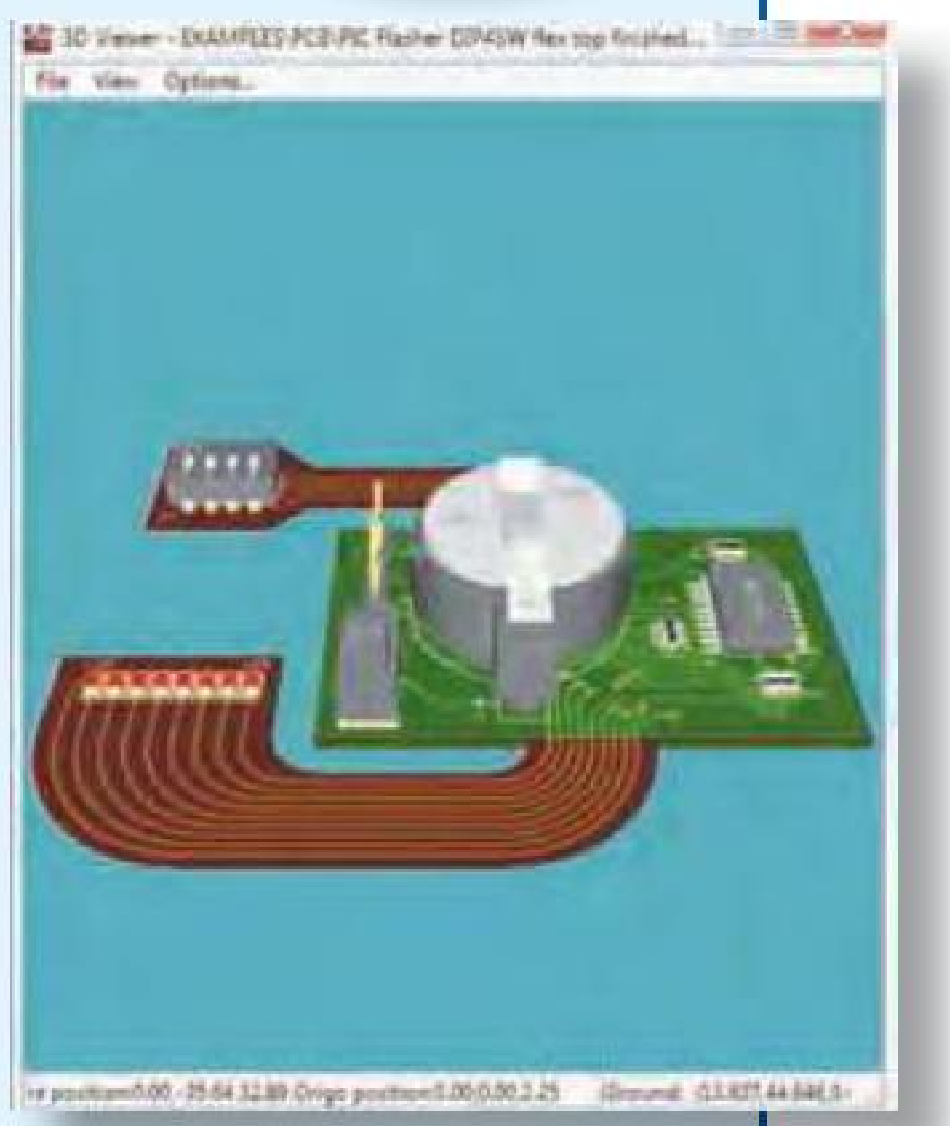

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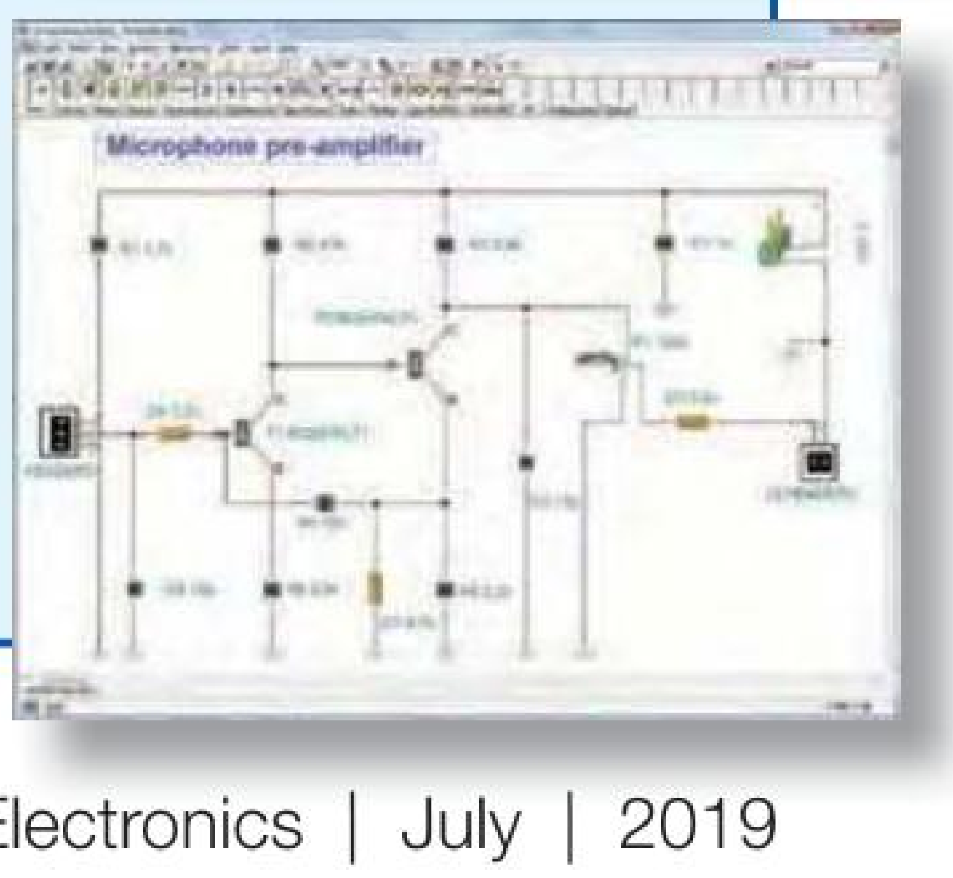

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(Formerly PICtutor)

Assembly for PICmicro microcontrollers V7.0 (previously known as PICtutor) by John Becker contains a complete course in programming the PIC16F84, 16F88 and 16F877a PICmicro microcontroller from Arizona Microchip. It starts with fundamental concepts and extends up to complex programs including watchdog timers, interrupts and sleep modes.

The CD makes use of the latest simulation techniques which provide a superb tool for learning: the Virtual PICmicro microcontroller, this is a simulation tool that allows users to write and execute MPASM assembler code for the PIC16F84 microcontroller on-screen. Using this you can actually see what happens inside the PICmicro MCU as each instruction is executed, which enhances understanding.

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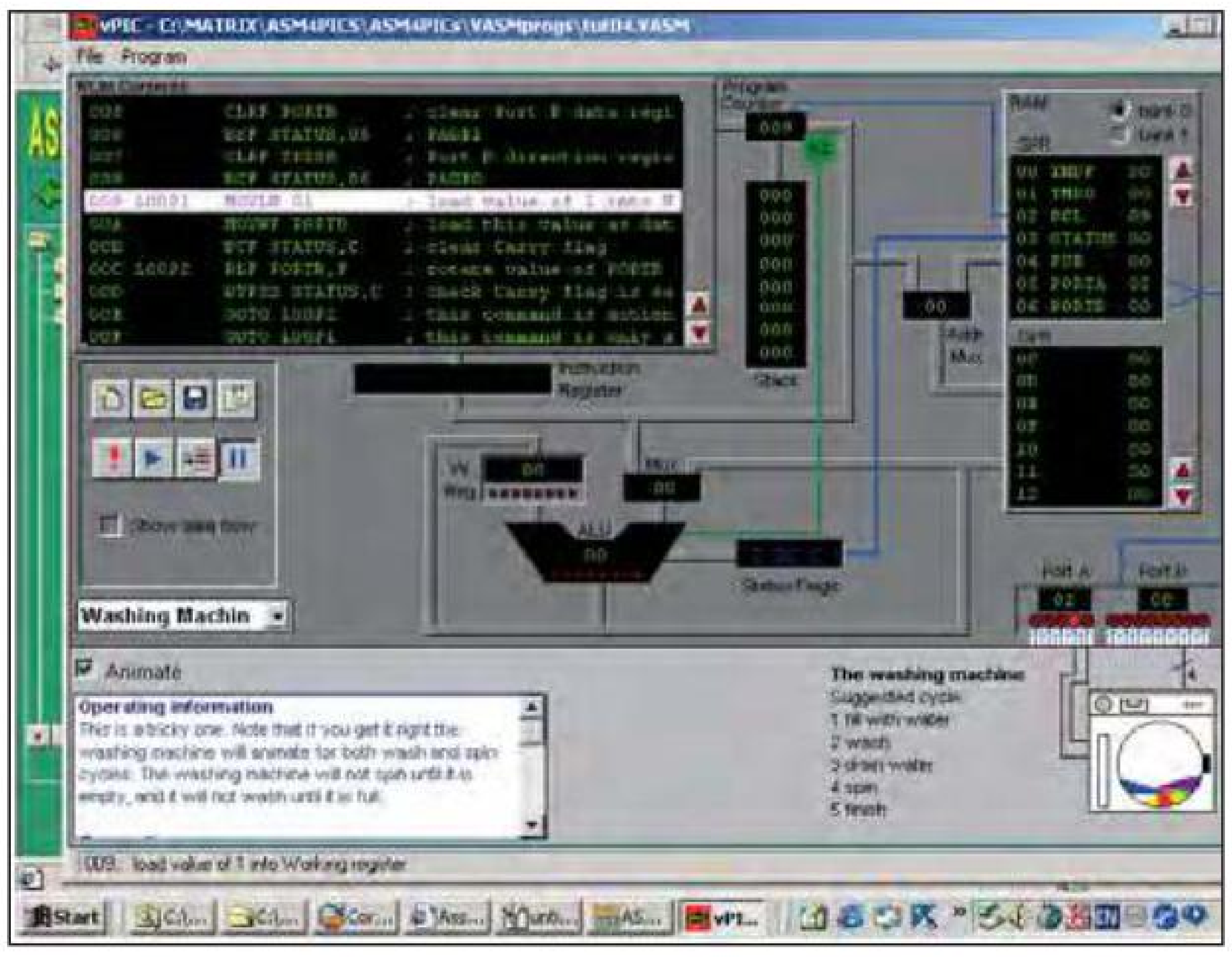

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Flowcode is a very high level language programming system based on flowcharts. Flowcode allows you to design and simulate complex systems in a matter of minutes. A powerful language that uses macros to facilitate the control of devices like 7-segment displays, motor controllers and LCDs. The use of macros allows you to control these devices without getting bogged down in understanding the programming. When used in conjunction with the development board this provides a seamless solution that allows you to program chips in minutes.

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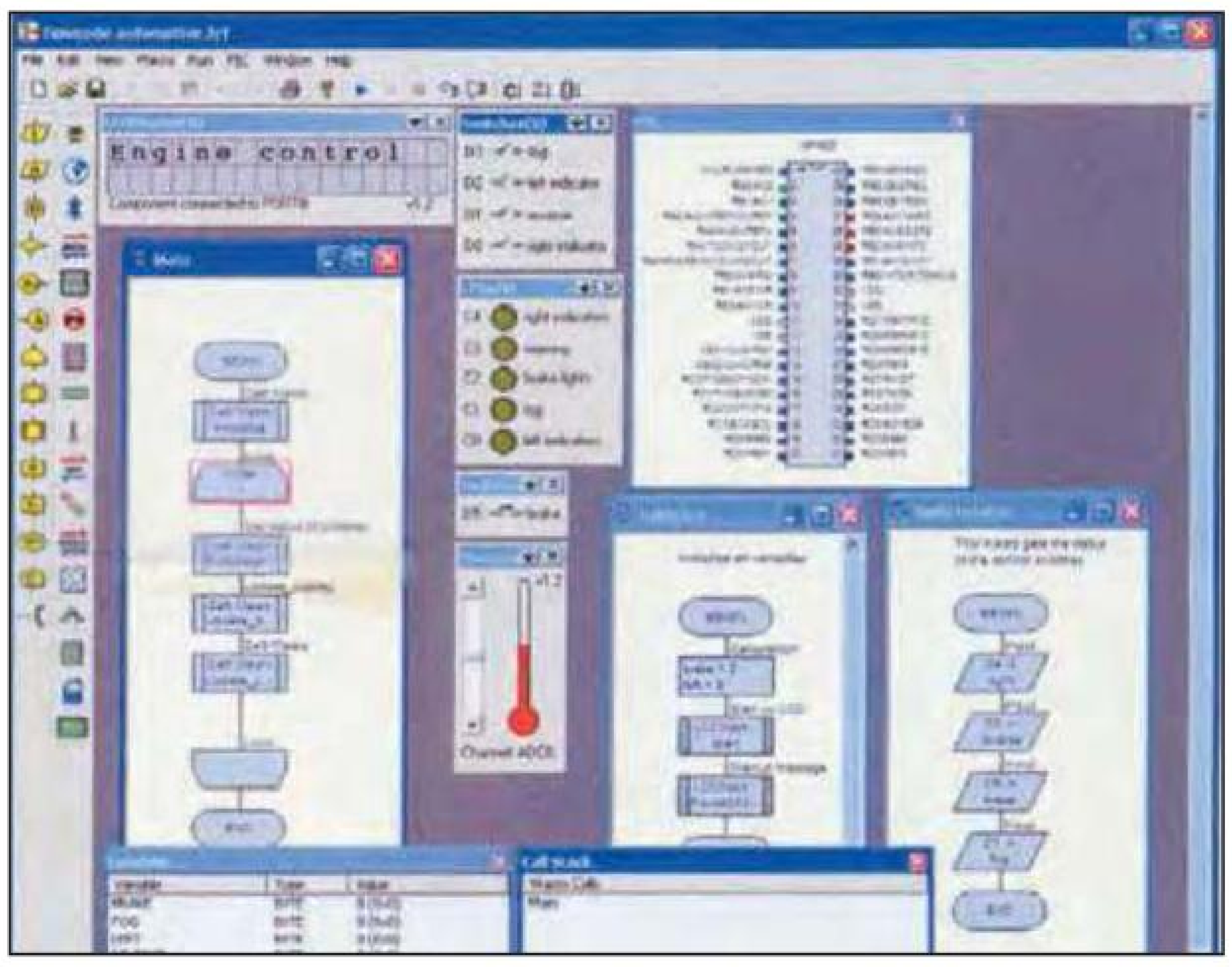

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ELECTRONICS TEACH-IN 2 CD-ROM
USING PIC MICROCONTROLLERS A PRACTICAL INTRODUCTION

This *Teach-In* series of articles was originally published in *EPE* in 2008 and, following demand from readers, has been collected together in the *Electronics Teach-In 2* CD-ROM.

The series is aimed at those using PIC microcontrollers for the first time. Each part of the series includes breadboard layouts to aid understanding and a simple programmer project is provided.

Also included are 29 *PIC N' Mix* articles, also republished from *EPE*. These provide a host of practical programming and interfacing information, mainly for those that have already got to grips with using PIC microcontrollers. An extra four part beginners guide to using the C programing language for PIC microcontrollers is also included.

The CD-ROM also contains all of the software for the *Teach-In 2* series and *PIC N' Mix* articles, plus a range of items from Microchip – the manufacturers of the PIC microcontrollers. The material has been compiled by Wimborne Publishing Ltd. with the assistance of Microchip Technology Inc.

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The CD-ROM also contains the complete *Electronics Teach-In 1* book, which provides a broad-based introduction to electronics in PDF form, plus interactive quizzes to test your knowledge, TINA circuit simulation software (a limited version – plus a specially written TINA Tutorial).

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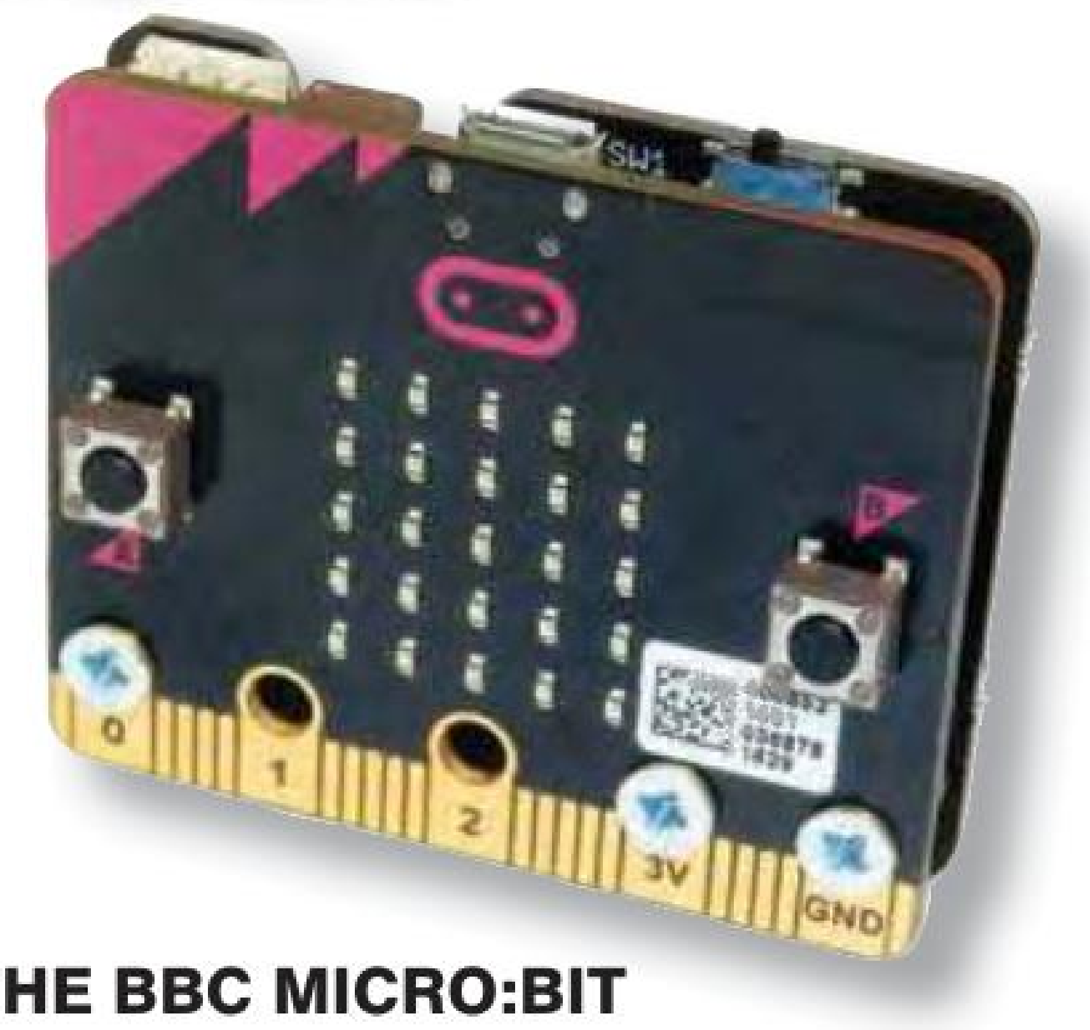
Introducing the BBC micro:bit



PYTHON CODING ON THE BBC MICRO:BIT

Jim Gatenby

Python is the leading programming language, easy to learn and widely used by professional programmers. This book uses MicroPython, a version of Python adapted for the BBC Micro:bit.

Among the many topics covered are: main features of the BBC micro:bit including a simulation in a web browser screen; various levels of programming languages; Mu Editor for writing, saving and retrieving programs, with sample programs and practice exercises; REPL, an interactive program for quickly testing lines of code; scrolling messages, creating and animating images on the micro:bit's LEDs; playing and creating music, sounds and synthesized speech; using the on-board accelerometer to detect movement of the micro:bit on three axes; glossary of computing terms.

This book is written using plain English, avoids technical jargon wherever possible and covers many of the coding instructions and methods which are common to most programming languages. It should be helpful to beginners of any age, whether planning a career in computing or writing code as an enjoyable hobby.

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Mike Tooley

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Mike Tooley's book will show you how the micro:bit can be used in a wide range of applications from simple domestic gadgets to more complex control systems such as those used for lighting, central heating and security applications. Using Microsoft Code Blocks, the book provides a progressive introduction to coding as well as interfacing with sensors and transducers.

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ARDUINO

Teach-In 2016

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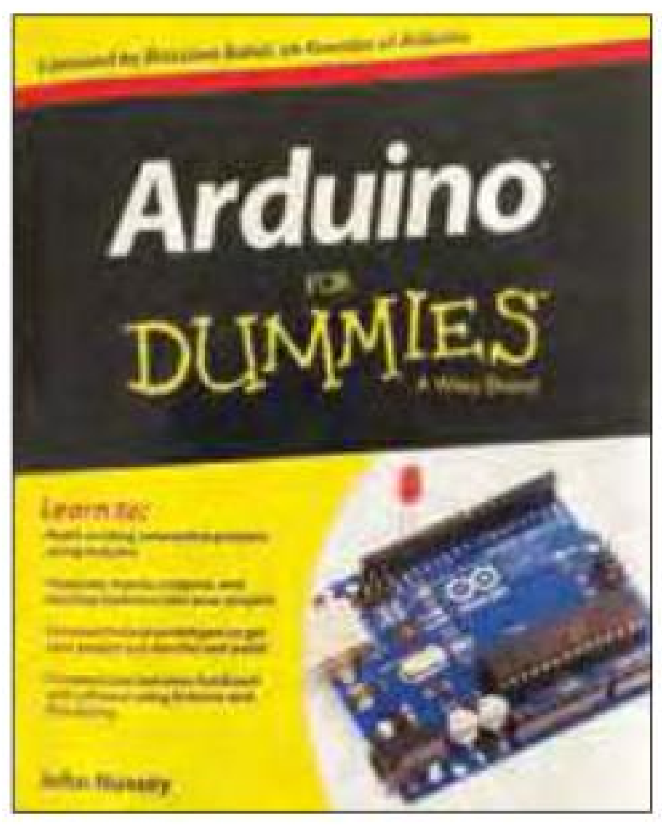

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John Nussey

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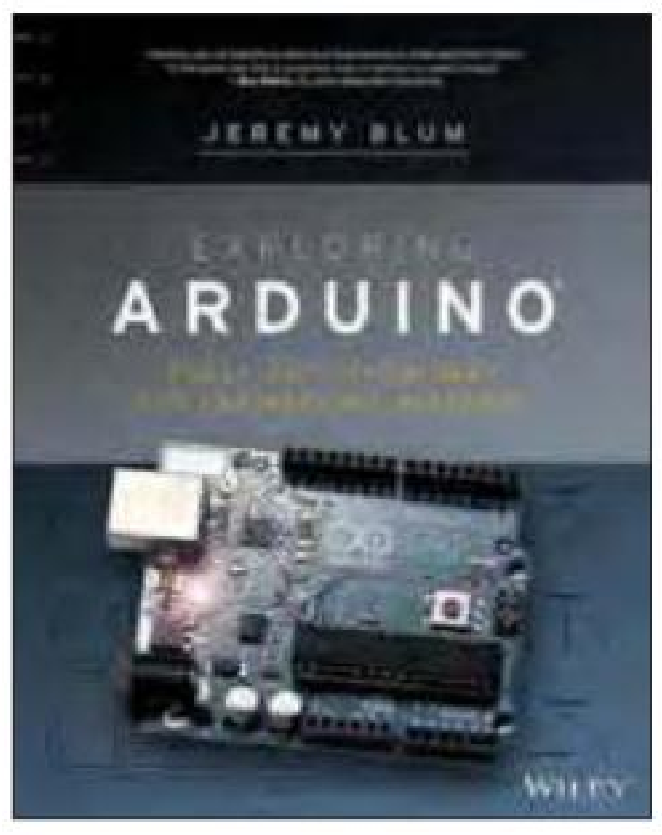

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Jeremy Blum

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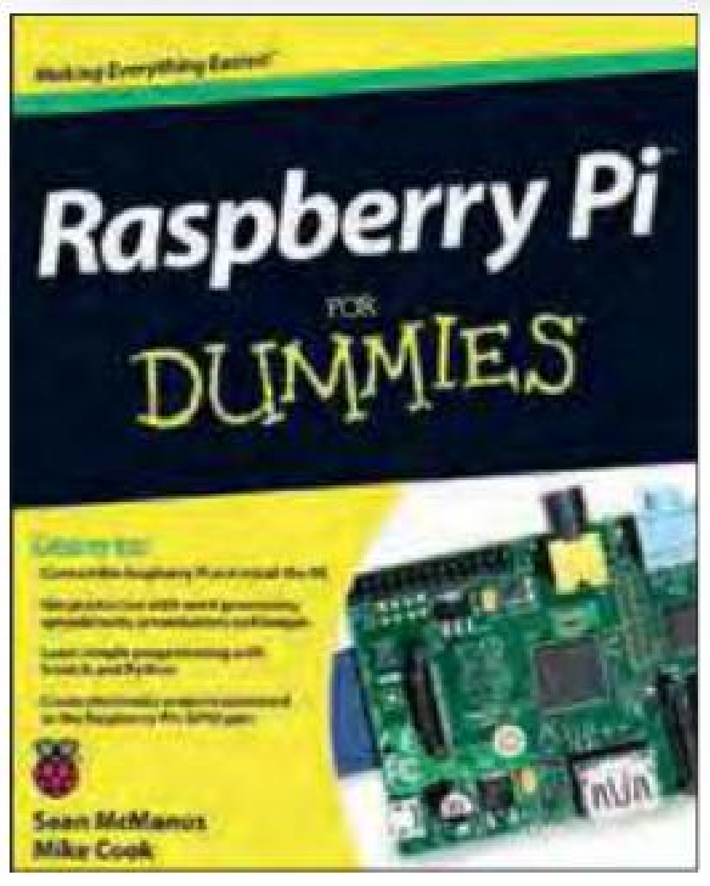

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Sean McManus and Mike Cook

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Mike & Richard Tooley

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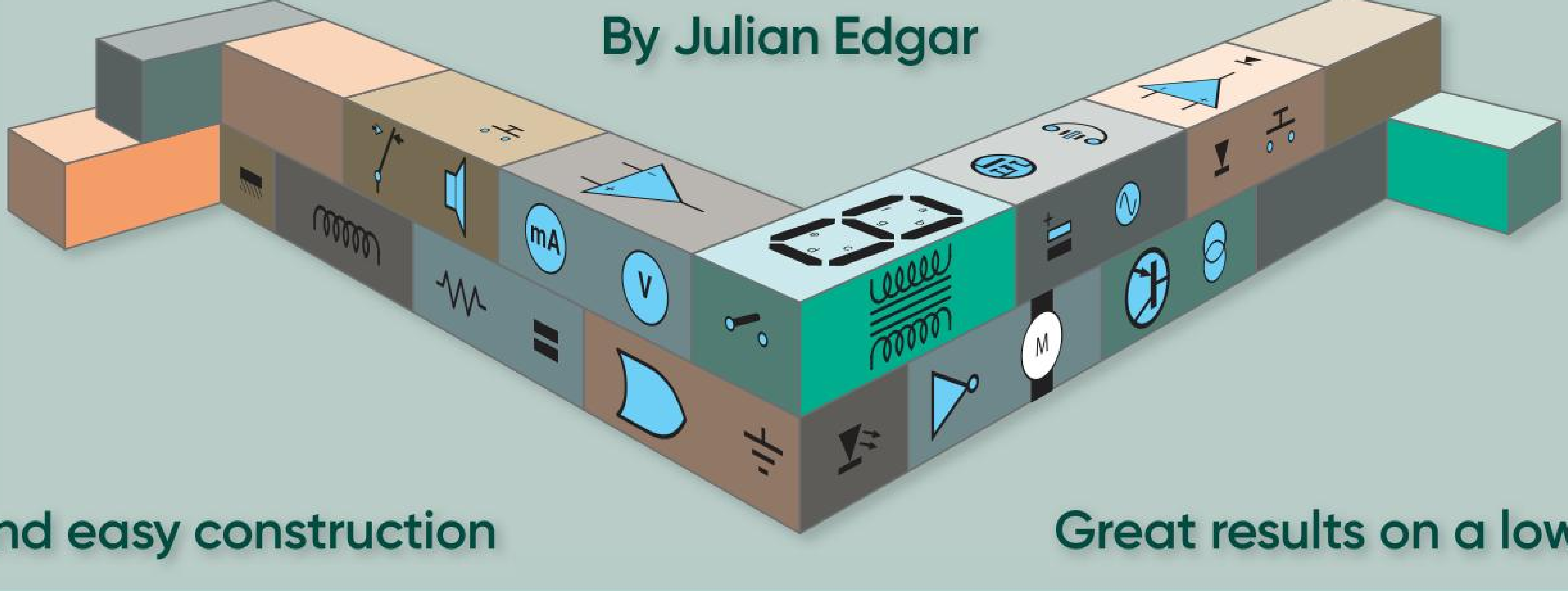

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Well, the good news is that with the availability of low-cost electronic modules and devices, spying is better than ever!

Vibration sensor

First off, you need to detect intruders breaking into your secret domain. One easy approach is to use a very sensitive vibration detector. Attach it to a door or window and it will alert you when either is moved. A nice example is item number 1347286 from Banggood – you'll pay under £4 for the module, delivered.

The board, shown in Fig.1, measures 63 × 27 × 18mm and has lots of connections – but we need only concern ourselves with five of them. Two are for ground and power – nominally 12V, but the board works fine at 9V (allowing portable use with a 9V battery). The other connections are for the on-board relay – common, normally open and normally closed. Two pots are provided – these adjust sensitivity and 'on' time. The pot closest to the relay is for sensitivity (anti-clockwise increases sensitivity) and the other pot adjusts 'on' time (clockwise rotation means longer delay).

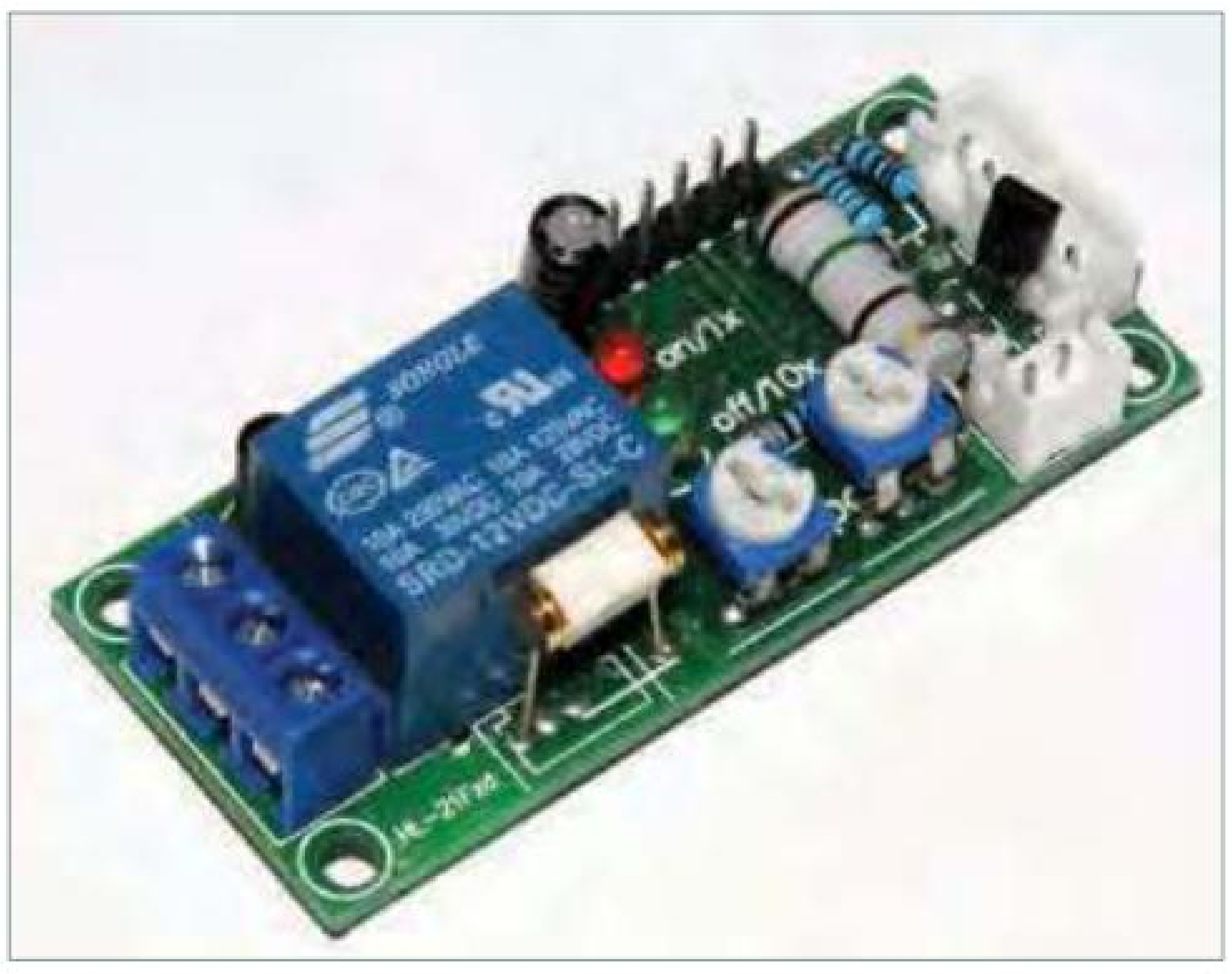

Fig.1. This very sensitive vibration detector uses a relay output, allowing easy switching of a buzzer or light. At its most sensitive, it cannot be moved without triggering the relay – perfect as a door alarm.

When the sensor on the module detects vibration, it lights a red LED and the relay is pulled in. It then stays pulled in for the period selected by the pot. The shortest possible delay is about 0.5s and the longest is over five minutes. When not activated, current draw at 9V is about 6mA – but if you want really low consumption, just remove the always-on green LED.

By wiring a buzzer or light through the relay, it's possible to have stealthy or loud alerts. At maximum sensitivity, it's impossible to move the board without triggering the relay. Note that the board appears to have a function where it cannot be triggered repeatedly in quick succession – presumably, this reduces the likelihood of false alarms.

In addition to kids' spying games and teenager 'room protection', this module would also be ideal as a motorcycle or bicycle alarm.

Video and still camera

It's not only a pen (Fig.2) – it's also a video and still camera! Costing just under £6 delivered from Banggood (item number 1326759), this covert still, video and audio recorder looks amazing value for money. And, for kids playing spies, it is. (But for more serious use, it's not.)

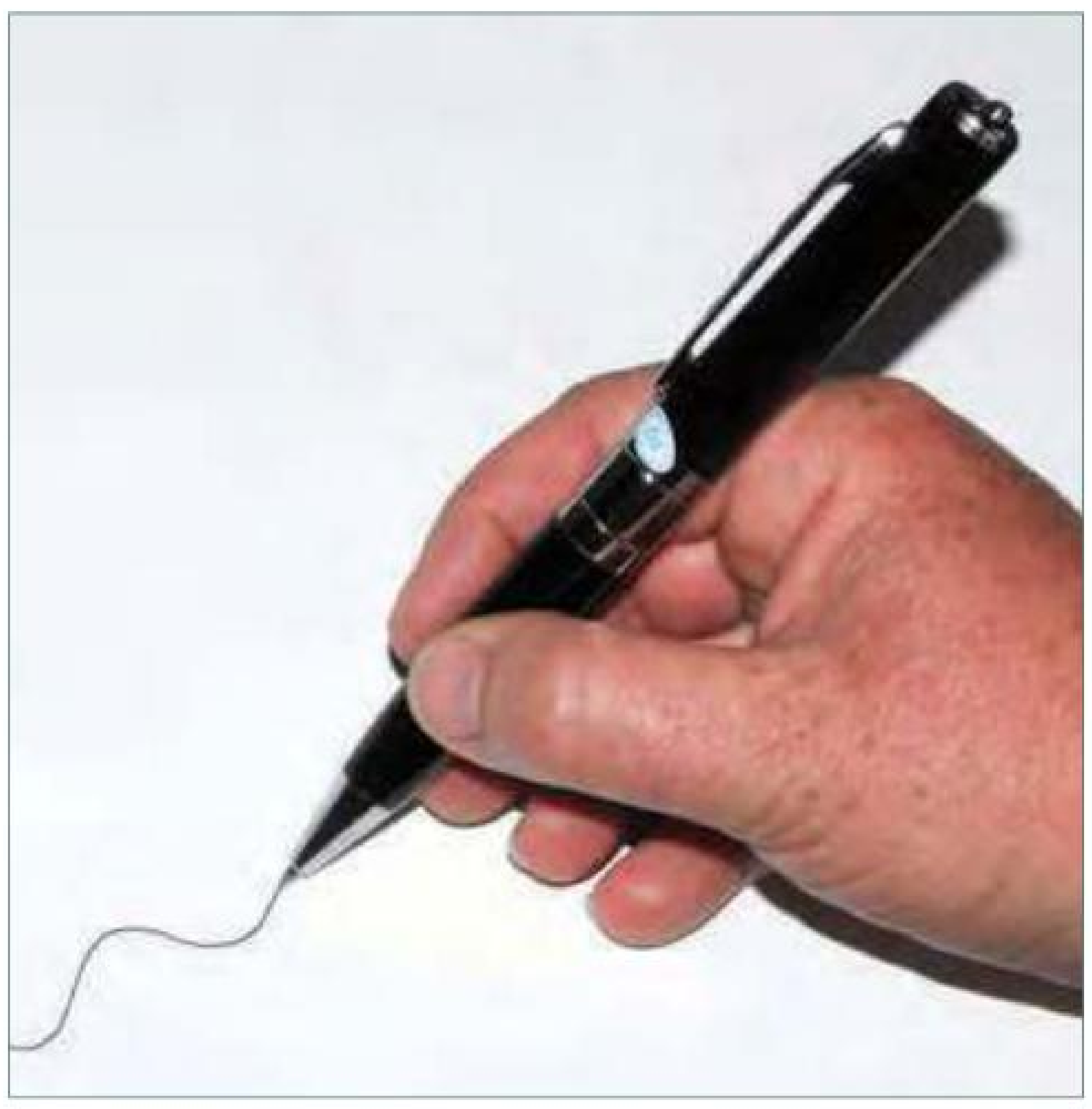

Fig.2. It may work as a pen – but it's also a video and still camera!

To use the 'pen', you'll need to supply an SD memory card – no recordings can be made without it (Fig.3). In operation, you press the end button for 2-3 seconds until a green indicator shows through a tiny hole. To record video, again press the end button for 2-3 seconds until the green indicator blinks several times, indicating that recording is about to begin. Pressing the button again ends the recording, which is

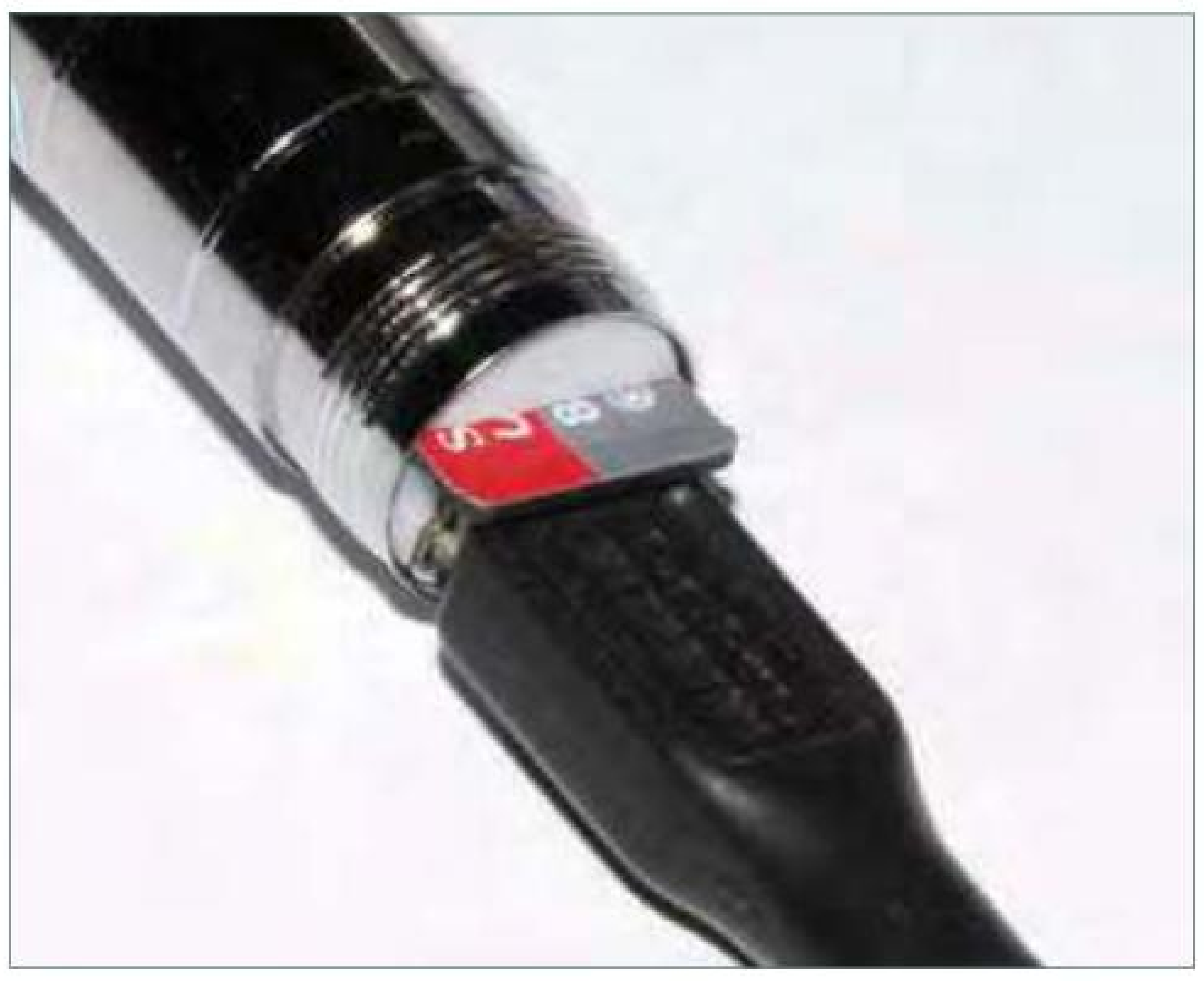

Fig.3. The end of the pen unscrews revealing access to the SD memory card and USB connections.

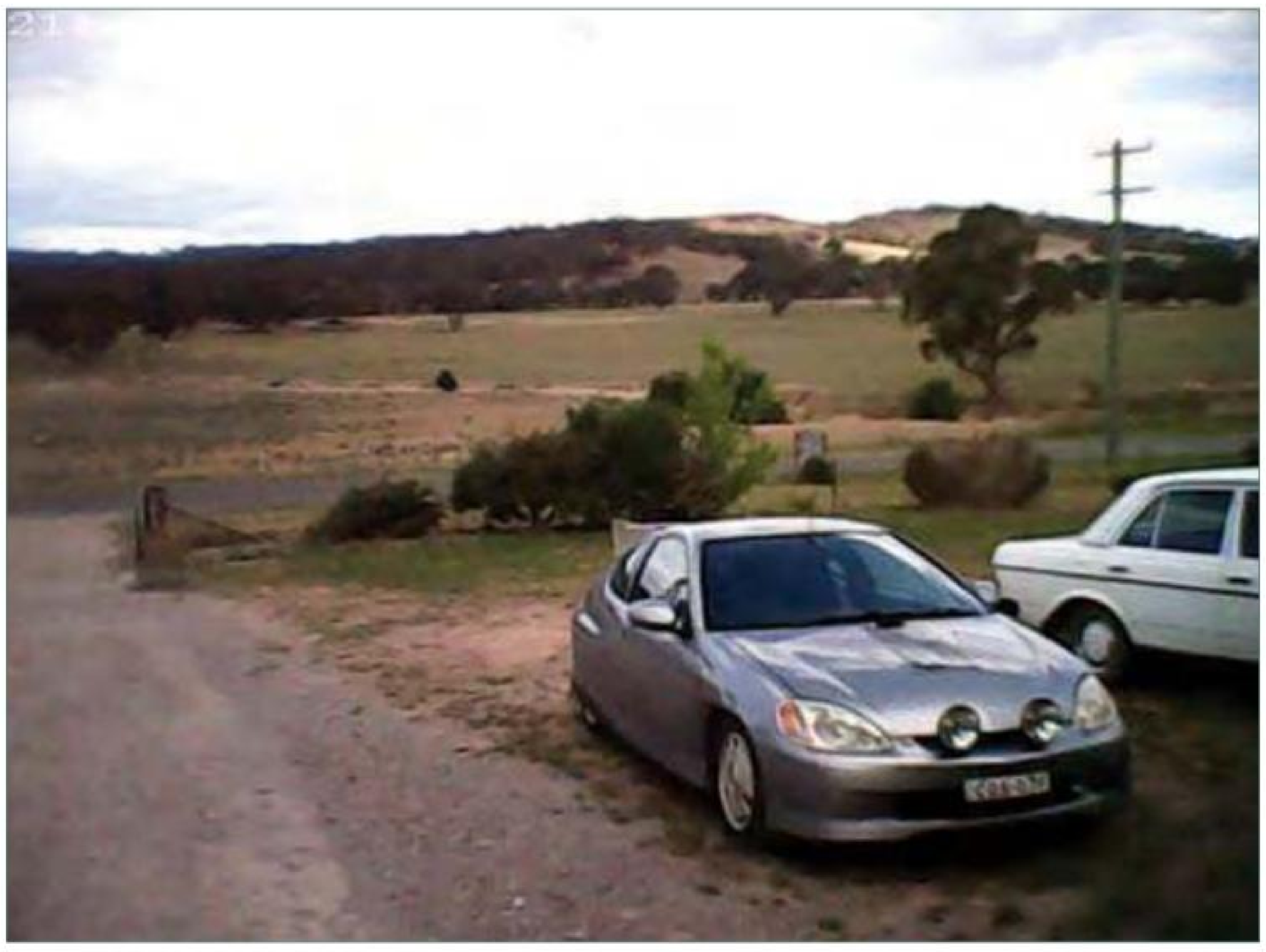

Fig.4. Un-retouched still pic taken by the pen camera. The quality of the still pics is a bit hit or miss – this is a good one!

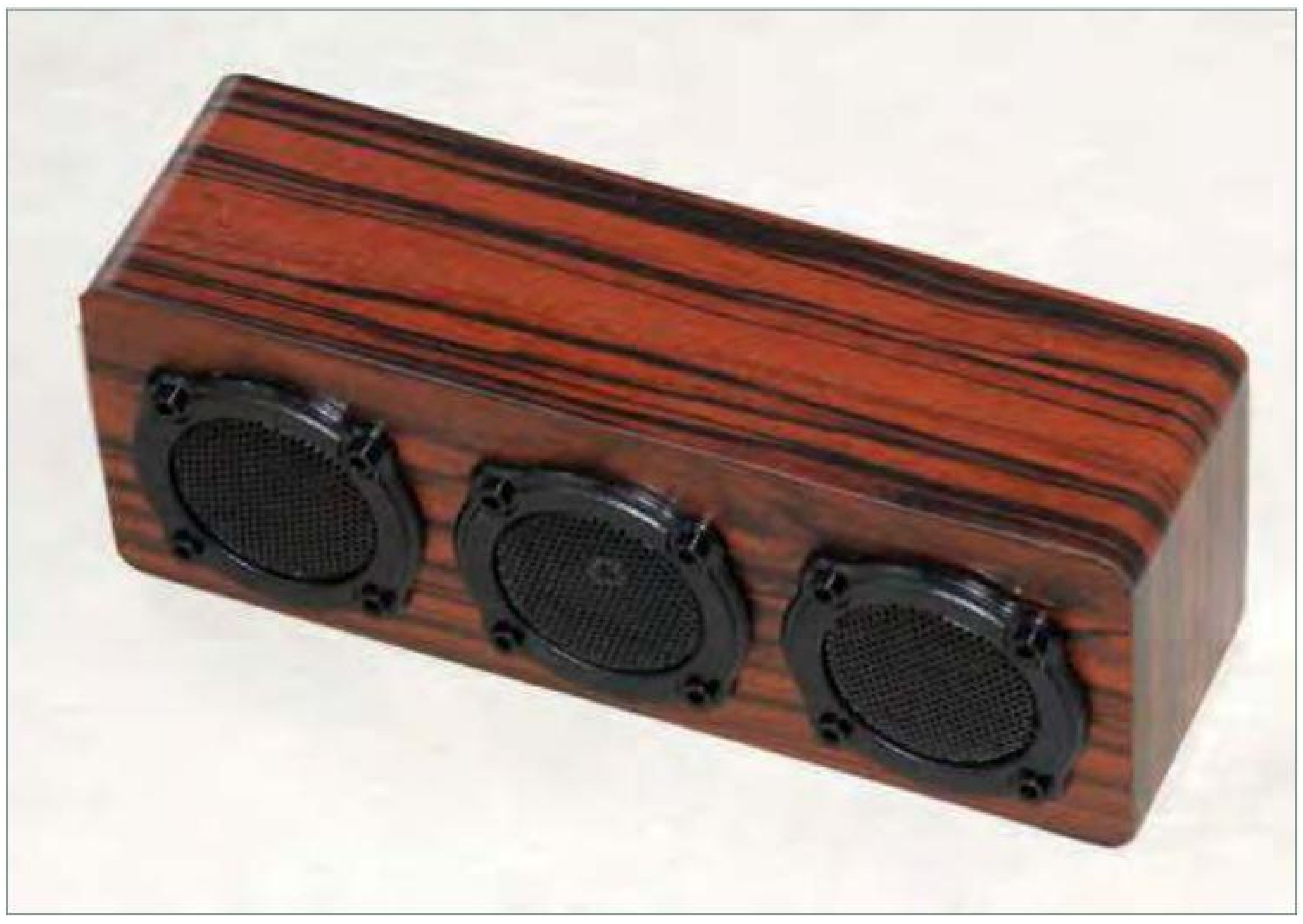

Fig.5. This stereo Bluetooth speaker uses two drivers and a passive radiator. The cost is low, playing time from the rechargeable battery good, and the sound is easily improved.

automatically saved to the card. Short presses of the end button take still pics.

Unscrewing the end of the pen allows you to plug in the supplied USB cable, with the data easily transferred from the memory card. Charging of the internal battery is also via a USB connection.

To be honest, video quality is pretty poor (720 × 480 resolution, with some smearing and image jumps) and the still camera has a resolution of 1280 × 960 (not the advertised 1280 × 1024 – see Fig.4). The lens is soft and the exposure is also a bit hit and miss. However, the audio is useable.

Nevertheless, the pen is good fun, although it certainly doesn't double as an always-there camera, or anything like that. But for a 12-year-old spy? Perfect! (Please note that covert recording, videography and/or photography may be illegal in some jurisdictions.)

Time for some music

And finally, what does the cool spy do when spying is over for the day? Maybe listen to some Bluetooth-streamed music while relaxing on the sofa with a long-haired white cat? Available for around £20, here is a stereo amplified speaker – see Fig.5. You can find it on banggood.com, ID 1321859. (It's also available on eBay under 'Kingneed Stereo Bluetooth Speaker', for example item 123333020716 – the price varies, but there it is typically £25 delivered.)

The size is 230 × 88 × 70mm and it weighs 570g. The unit uses a 1.2Ah battery and has a claimed playing time on a full charge of about eight hours.

The system is a bit of a mixed bag, but the reason I've included it here is that it's easy to improve its sound. The amplifier is a bit noisy (there's plenty of hiss) but I decided to leave that aspect alone. Bluetooth connection is good once established, but to re-link, you may need to 'forget this device' on the phone and then switch Bluetooth on and off again to re-find the speaker.

The box appears to have three drivers, but in fact the centre one is a passive radiator – a weighted diaphragm. In effect this makes the enclosure act a bit like a ported design, but typically with a longer port than could be fitted into the box.

Easy upgrades

Two modifications considerably improve the sound. The first is to fill the enclosure with fluffy polyester – I used quilt wadding, as shown in Fig.6. Only a small amount is needed – just enough that the enclosure is loosely packed. To get the wadding into the box, it's easiest to remove the passive radiator, thus leaving a large opening through which the material can be fed.

To remove the passive radiator, use a sharp knife to carefully lever off the grille and surround (the Allen key bolts are fake). The passive radiator does not use a frame – it just sits in the recess and can be carefully lifted around its edges before being removed. Fill the box with the wadding, and then, using contact adhesive or similar, re-glue the edge of the passive radiator back into place.

The wadding gives the effect of increasing box size, and also prevents reflections within the enclosure. The sound is immediately more restrained in its midrange.

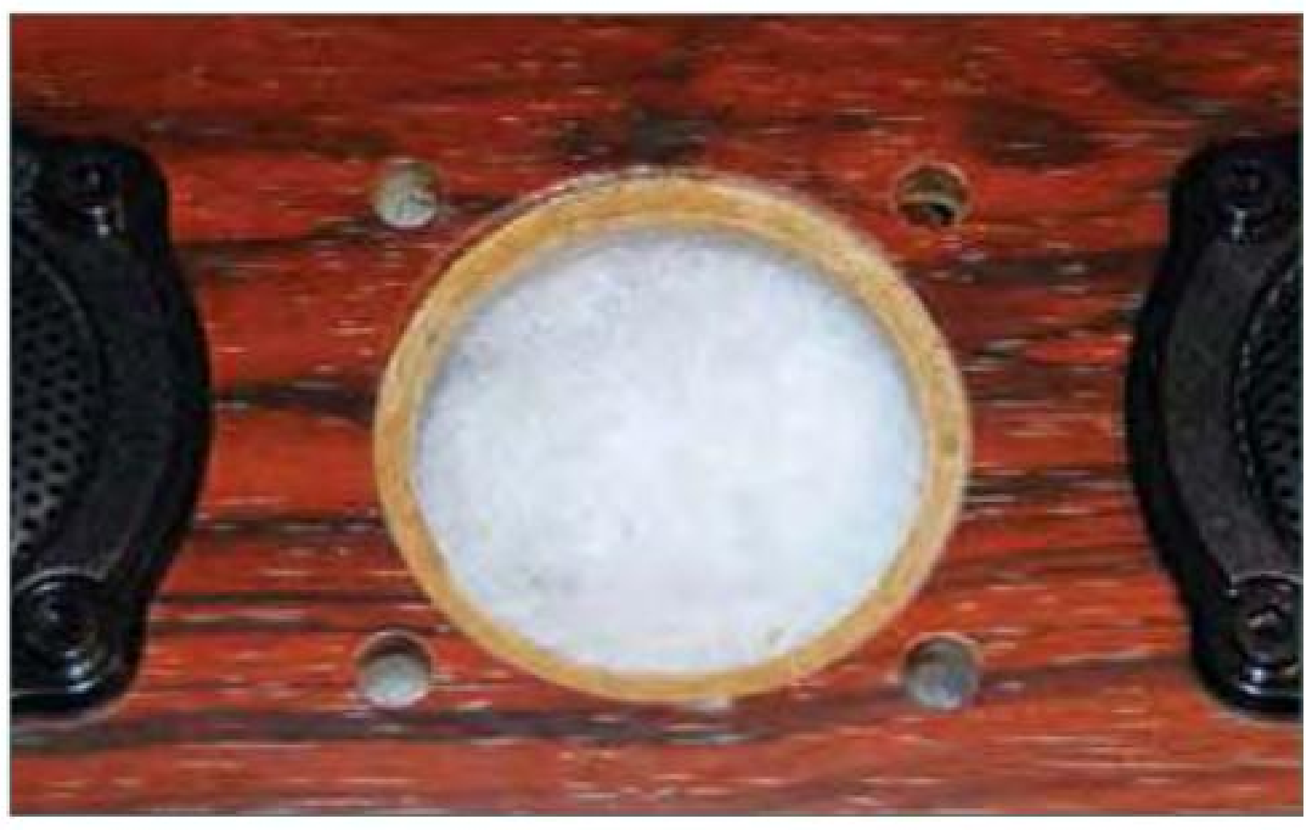

Fig.6. By carefully removing the passive radiator, an opening is created through which fluffy quilt wadding can be inserted. This improves the quality of the mid-range.

By changing the weight of the passive radiator diaphragm, you can alter its resonant behaviour. I experimented with different weights (washers attached temporarily with tape) and settled on a small washer – the type used with a 4mm screw. The washer was attached to the centre of the passive radiator diaphragm with contact adhesive. Finally, when you're not charging the device, place some tape over the rear micro USB port – without this, air can flow in and out of this hole and distinctly change the bottom-end frequency response.

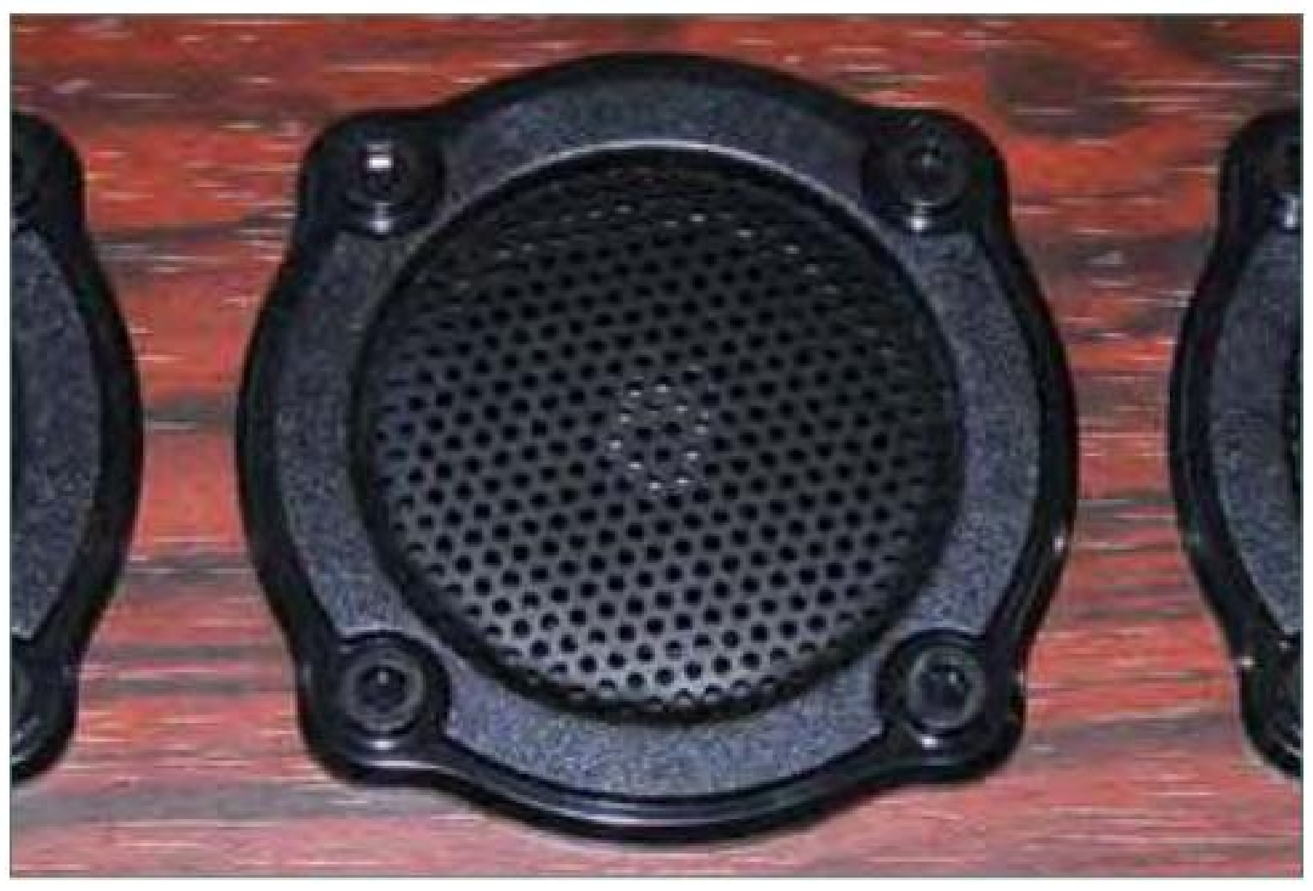

Fig.7. Just visible here is a small washer glued to the passive radiator. This changes the resonant behaviour of the radiator, improving the bottom-end response a little.

These modifications give reasonably smooth response down to about 80Hz (not bad with 50mm drivers!) and quite competent midrange and treble.

Next month

In the August issue we have the *The World's Best DIY Car Immobiliser…* and it's simple and cheap, too! This little project is perfect for cars, motorcycles and agricultural equipment.

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ADVERTISING INDEX

CRICKLEWOOD ELECTRONICS	27
ESR ELECTRONIC COMPONENTS	27
HAMMOND ELECTRONICS Ltd	8
JPG ELECTRONICS	80
LASER BUSINESS SYSTEMS	57
MICROCHIP	Cover (ii), Cover (iii) & 5
PEAK ELECTRONIC DESIGN	Cover (iv)
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Next Month – in the August issue

Arduino Brainwave Monitor

This project detects the tiny signals produced by your brain, displays them on a computer screen and even saves and prints them for future use. It's based on an Arduino Nano and connects to a PC using a standard USB cable.

Super Digital Sound Effects Module

Despite its miniscule size this is a truly powerful sound effects module. It can be loaded with dozens of sound effects or audio tracks, short or long, with a virtually unlimited playback time and advanced controls – you'll be amazed!

Control your computer with an infrared remote control

Want to connect a PC to your TV for playing videos, music, games, viewing photos, web browsing and so on? This is known as a home theatre PC (HTPC), but operating a keyboard and mouse from the couch is clumsy. Why not use our infrared controller for important functions like play, pause, next track?

Watchdog Alarm!

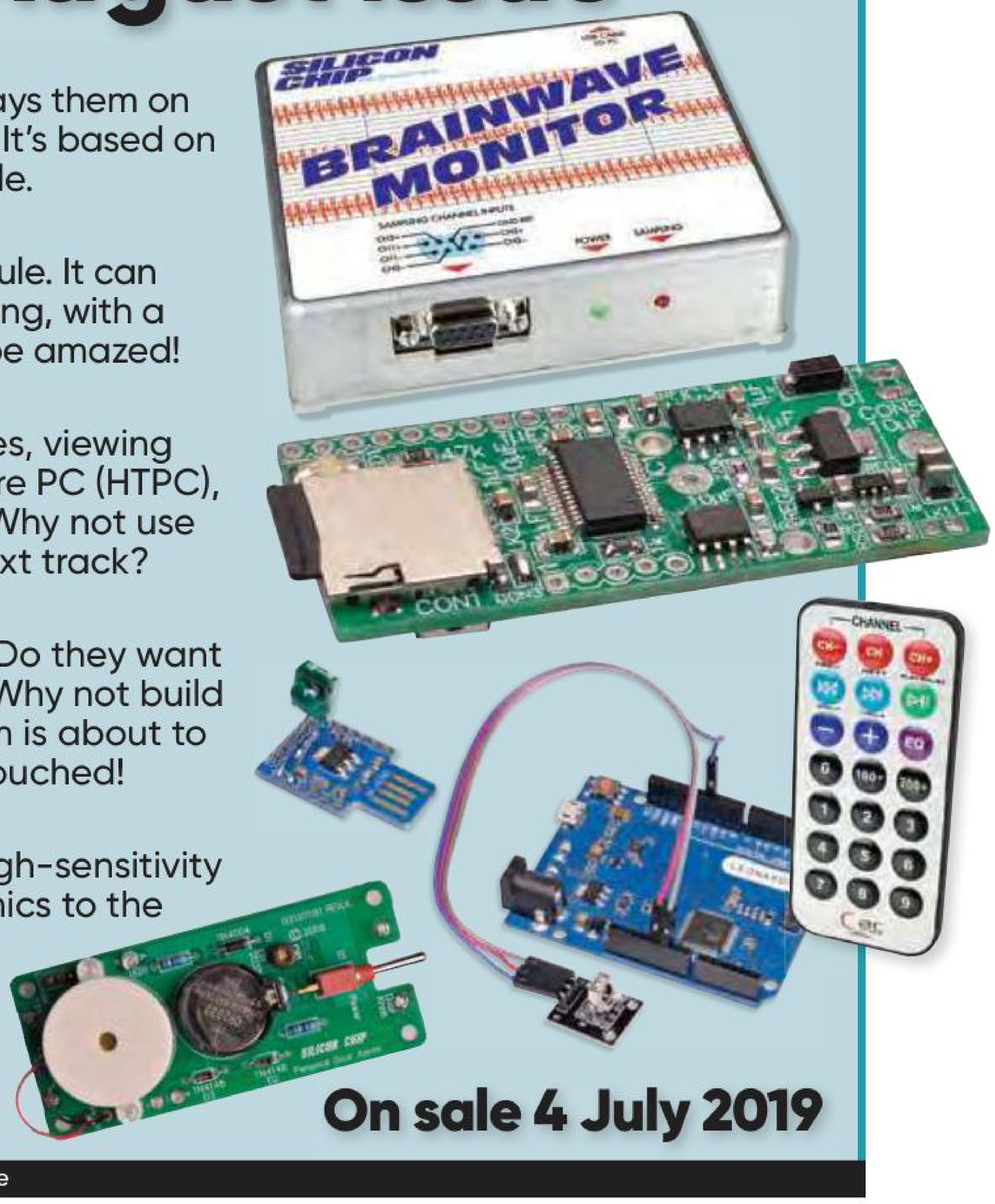
Do you have children or grand-children who are very territorial? Do they want extra security against invasion of their rooms by pesky siblings? Why not build a personal security alarm so they can be alerted when their room is about to be invaded? It will sound an alarm as soon as the door knob is touched!

PE Theremin – Part 3

Next month, we'll finish Jake Rothman's fascinating exercise in high-sensitivity analogue design – the *PE Theremin*. Everything from the electronics to the aerials and casing will be comprehensively covered.

PLUS!

All your favourite regular columns from *Cool Beans*, *Make it with Micromite*, *Circuit Surgery* and *Electronic Building Blocks* to *PIC n' Mix*, *Audio Out*, *Techo Talk* and *Net Work*.



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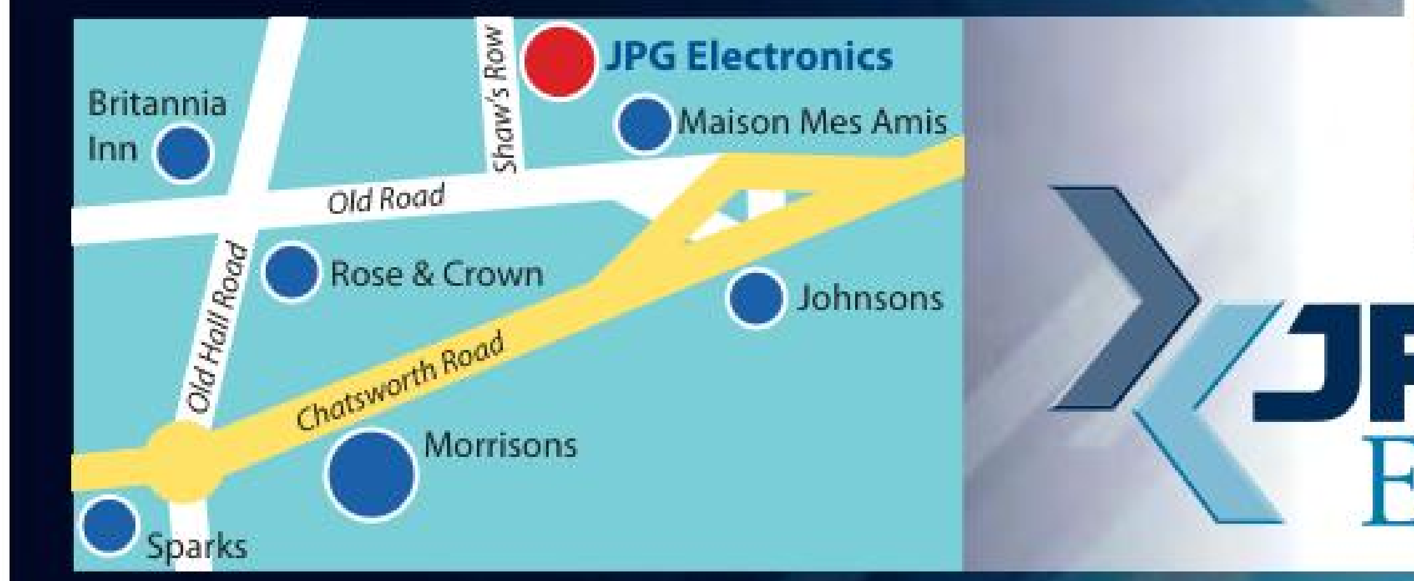

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Development Tool of the Month!

Explorer 16/32 Development Kit

EXPLORER 16/32

Part Number
DM240001-3

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The development kit comes with Explorer 16/32 main development board, PIC24FJ1024GB610 PIM (MA240023), USB A to micro-B cable, and USB A to Type-C Cable. For out of the box experience, Explorer 16/32 Development Kit is the right choice that comes with all the necessary components to get started with the evaluation and prototyping right away!

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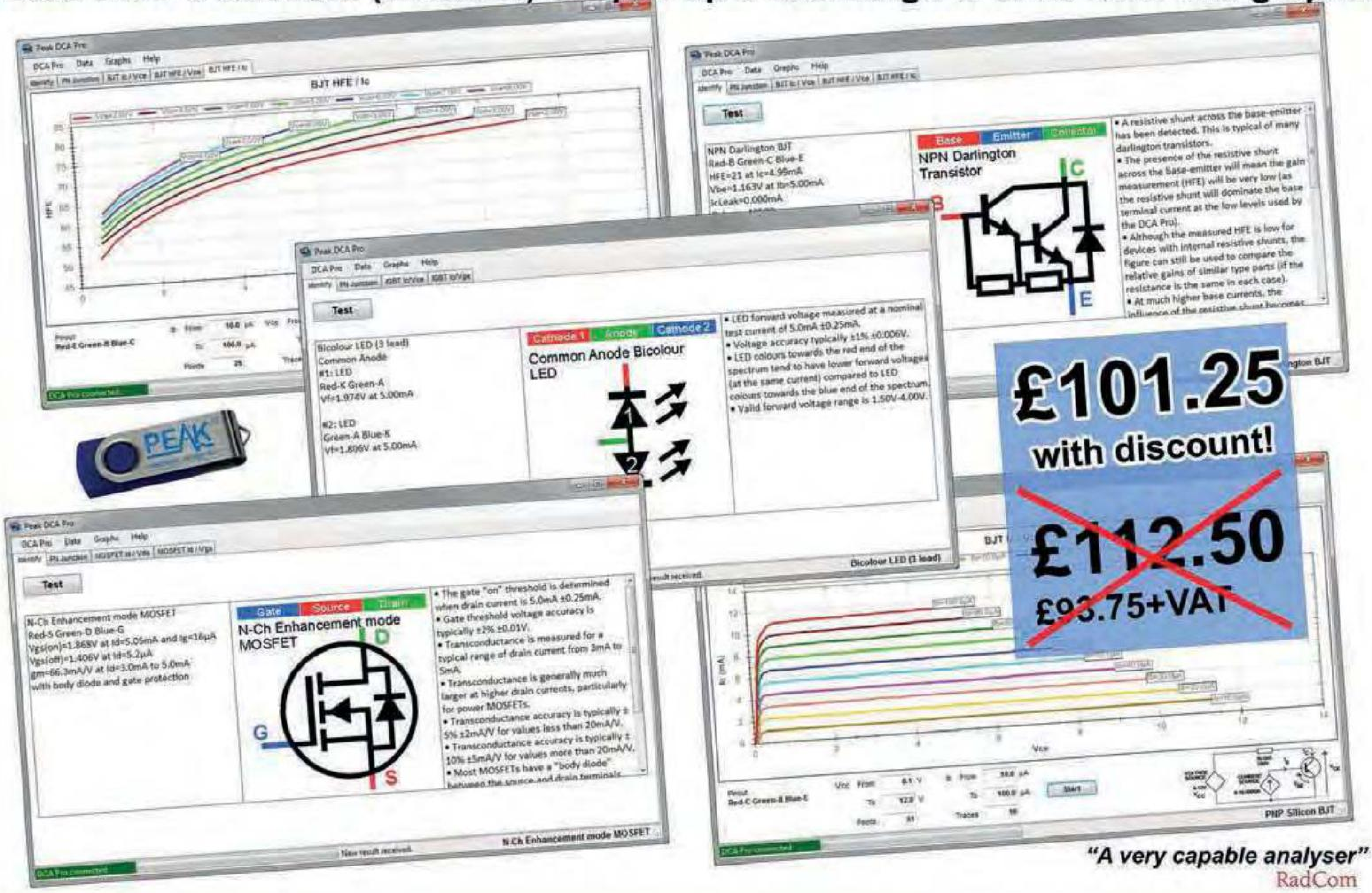
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E
Cathode 1
Anode
Cathode 2
Common Anode Bicolour LED
1
2
Gate
Source
Drain
N-Ch Enhancement mode MOSFET
G
D
S
Bicolour LED (3 lead)
N Ch Enhancement mode MOSFET
New result received.
DCA Pro connected
PNP Silicon BJT
PEAK

NPN Darlington BJT
Red-B Green-C Blue-E
HFE=21 at Ic=4.99mA
Vbe=1.163V at Ib=5.00mA
IcLeak=0.000mA

- A resistive shunt across the base-emitter has been detected. This is typical of many darlington transistors.
- The presence of the resistive shunt across the base-emitter will mean the gain measurement (HFE) will be very low (as the resistive shunt will dominate the base terminal current at the low levels used by the DCA Pro).
- Although the measured HFE is low for devices with internal resistive shunts, the figure can still be used to compare the relative gains of similar type parts (if the resistance is the same in each case).
- At much higher base currents, the influence of the resistive shunt becomes

Bicolour LED (3 lead)
Common Anode
#1: LED
Red-K Green-A
Vf=1.974V at 5.00mA

#2: LED
Green-A Blue-K
Vf=1.806V at 5.00mA

- LED forward voltage measured at a nominal test current of 5.0mA ±0.25mA.
- Voltage accuracy typically ±1% ±0.006V.
- LED colours towards the red end of the spectrum tend to have lower forward voltages (at the same current) compared to LED colours towards the blue end of the spectrum.
- Valid forward voltage range is 1.50V-4.00V.

N-Ch Enhancement mode MOSFET
Red-S Green-D Blue-G
Vgs(on)=1.863V at Id=5.05mA and Ig<16µA
Vgs(off)=1.406V at Id=5.2µA
gm=66.3mA/V at Id=3.0mA to 5.0mA
with body diode and gate protection

- The gate "on" threshold is determined when drain current is 5.0mA ±0.25mA.
- Gate threshold voltage accuracy is typically ±2% ±0.01V.
- Transconductance is measured for a typical range of drain current from 3mA to 5mA.
- Transconductance is generally much larger at higher drain currents, particularly for power MOSFETs.
- Transconductance accuracy is typically ± 5% ±2mA/V for values less than 20mA/V.
- Transconductance accuracy is typically ± 10% ±5mA/V for values more than 20mA/V.
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